AD 401303

THE CINCINNATI MILLING MACHINE CO.

CINCINNATI 9 OHIO U.S.A.

P. WILLARD CRANE
VICE PRESIDENT

Armed Services Technical
Information Agency
ASTIA (TISIA-2)
Arlington Hall Station
Arlington 12, Virginia

At the request of the Fabrication Branch, Manufacturing Technology Laboratory of the Aeronautical Systems Division, Air Force Systems Command, we are forwarding herewith a copy of "Final Report on High Temperature Machining Methods". This report covers all work performed from September 5, 1959, to October 11, 1962.

The work reported in this document has been made possible through cooperation and sponsorship of the Aeronautical Systems Division, Air Force Systems Command under contract AF33(600)40066.

Your review and comments on this report are earnestly invited. They may be directed to the writer or to Air Force Systems Command, Air Force Systems Command, Aeronautical Systems Division, Attention: ASRCTF, Wright-Patterson Air Force Base, Ohio.

Sincerely,

P. W. Crane

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AIR FORCE SYSTEMS COMMAND
UNITED STATES AIR FORCE
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

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Project Number - 7-704 Report Number - ASD TDR-63-125
Project Title - "High Temperature Machining Methods"

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FOREWORD

This Final Technical Documentary Report covers all work performed under contract AF33(600)40066 from 5 September 1959 to 11 October 1962. The manuscript was released by the author on 23 January 1963 for publication as an ASD Technical Documentary Report.

This contract with the Cincinnati Milling and Grinding Machines, Inc. of Cincinnati, Ohio, was initiated under ASD Manufacturing Technology Laboratory Project 7-704 "High Temperature Machining Methods". Included is the report of effort prescribed by a supplemental agreement to the contract and identified as ASD Project 7-704 A. It is being administered under the direction of Mr. Floyd Whitney of the Fabrication Branch (ASRCTF), Manufacturing Technology Laboratory, AFSC Aeronautical Systems Division, Wright-Patterson Air Force Base, Ohio.

Mr. William Pentland, Research Supervisor, was the engineer in charge of this program until 2 September 1960. During the period 2 September 1960 through 10 August 1962 Mr. Jens L. Wennberg was the engineer in charge. Since that date Mr. I. A. Dickter, Research Supervisor, has been in charge. Others who cooperated in this investigation and preparation of the report have been Mr. Russell F. Henke, Research Engineer, Mr. Clarence L. Mehl, Senior Research Engineer, Mr. E. J. Krabacher, Senior Research Supervisor, and Dr. M. Eugene Merchant, Director of Physical Research. This project has been given Cincinnati Milling and Grinding Machines, Inc. internal numbers 412N467, 412N468, 412N469, and 417N887.

The primary objective of the Air Force Manufacturing Methods Program is to develop on a timely basis manufacturing processes, techniques and equipment for use in economical production of USAF materials and components. This program encompasses the following technical areas:

> Rolled Sheet, Forgings, Extrusions, Castings, Fiber and Powder Metallurgy, Component Fabrication, Joining, Forming, Materials Removal, Fuels, Lubricants, Ceramics, Graphites, Non-metallic Structural Materials, Solid State Devices, Passive Devices, Thermionic Devices.

Your comments are solicited on the potential utilization of the information contained herein as applied to your present or future production programs. Suggestions concerning additional Manufacturing Methods development required on this or other subjects will be appreciated.

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ABSTRACT **ASD-TDR-63-125**
Final Technical Documentary Report **January 23, 1963**

HIGH TEMPERATURE MACHINING METHODS

Irving A. Dickter
Clarence L. Mehl
Russell F. Henke

The Cincinnati Milling Machine Co.

Hot machining can reduce the cost of manufacturing parts from many high strength steels, precipitation hardening stainless steels, and nickel and cobalt based alloys. Selection of parts with suitable materials, and proper planning of set-up and sequence of operations, materially influences the final cost. Manufacturing costs of aerospace parts when hot machined from heat treated AISI 4340 and Ph 15-7 Mo steels were reduced up to 36% when compared to conventional machining.

Radio-frequency induction and resistance heating techniques were developed and proved practical for heating magnetic materials, while the inert tungsten arc torch was more satisfactory for non-magnetic materials.

Most high strength metals will show a significant increase in tool life and permissible metal removal rates at elevated temperatures. Hot machining of 6 Al 4 V, 13 V 11 Cr 3 Al titanium alloys and refractory metals and alloys, achieved only limited success.

While some metallurgical changes were observed on the hot machined nickel and cobalt based alloys, these changes were not severe or extensive.

No excessive safety or health hazards are involved.

PUBLICATION REVIEW

This report has been reviewed and is approved.

FOR THE COMMANDER:

JACK R. MARSH
Assistant Chief
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INTRODUCTION

The advent of widespread use of high strength and thermal resistant materials has severely increased the difficulties in manufacturing the complex parts required by aerospace requirements.

One proposed solution to these difficulties was elevated temperature machining, i.e. to elevate the workpiece temperature, so as to reduce its strength and improve its machinability.

Since 1957, The Cincinnati Milling Machine Co. has been conducting research to evaluate and develop hot machining techniques. The sponsorship and support of this project by the Aeronautical Systems Division, beginning in September 1959, has meant that the scope of the research has been greatly broadened. This report, then, describes the work on elevated temperature machining conducted over the last three years.

HISTORICAL BACKGROUND

It appears that the credit for the initial use of hot machining must be given to Benjamin C. Tilghman of Philadelphia, Pennsylvania, who in 1889 was awarded a Letters Patent on "Cutting Metal by Electricity"(65)*. Tilghman used resistance heating with the tool (a rotating disk to rub away the metal) as one electrode. Thus, the electric current is concentrated and the "metal is heated to the desired degree at the point where it is being operated upon and not elsewhere".

We do not find any significant uses of hot machining in the immediate years which followed this work. The use of "hot sawing" in the steel mills can be said to be an early application of the advantages to be gained by elevated temperature machining.

* Numbers in parenthesis refer to the Bibliography.

Indications are that earliest modern applications of hot machining might have been made by the Krupp Steel Works in Germany during World War II scalping steel billets at approximately 1800°F to take advantage of the softened condition of the metal at that temperature.

However, the idea of intentionally heating the workpiece for better machinability was recorded by Dr. H. W. Gillett in a Battelle interoffice memorandum dated May 10, 1944. In preliminary studies, it was shown that elevated temperatures improved the machining characteristics of materials which were otherwise difficult or impossible to machine. As a result of this work, the Warner and Swasey Company sponsored a research investigation at Battelle Memorial Institute on "The Machining of Metals at Elevated Temperatures"[7]. The research was carried out during the period, March 1945 to November 1946.

Early in 1946, Sam Tour and Company, Inc. submitted a proposal to the U.S. Navy Department, Bureau of Ships for Research in the area of "Hot Spot Machining"[20, 35, 68, 69]. In December 1946, a patent (No. 2412797) was issued to M. Berliner, later transferred to Induction Machine, Inc., for hot machining with induction heating.

Simultaneously, but independently, tests were conducted at Kearney and Trecker Corp. by Schmidt and Roubik to evaluate hot milling.

In 1949, A. O. Schmidt and J. R. Roubik published the results of their investigations[59, 60] in the area of hot face and slab milling of high strength die blocks. They indicated that these materials could be milled at higher cutting speeds and feed rates for equivalent tool life. Lower power consumption was also reported. An oxy-acetylene flat surface torch was used for heating.

A series of six articles were published by Sam Tour, et al.[20, 35, 68, 69] in 1949 and 1950 on the work conducted by them under a Navy contract. S816 alloy, a "V" grade nickel steel and various grades of carbon steel were turned with both flame and induction heating. Results showed an increase in removal rate and a decrease in tool forces. Surface finish was found to be superior at elevated temperatures. Induction heating was reported to have no effect on the metallurgy of the finished part.

The work reported by Armstrong, Cosler, and Katz of Battelle Memorial Institute in 1950 indicated a two-fold increase in tool life by heating the workpiece to 400°F and showed that high temperature alloys, including vitallium, machine freely at temperatures from 700° to 2000°F. Chip formation and surface finish were improved by the elevated temperature. Austenitic manganese steel and fully hardened high speed steel were found to machine easily at 1200°F. An arc heating method was developed which permitted continuous heating while machining without heating the workpiece throughout. The investigation included both AC and DC arcs stabilized by a superimposed magnetic field.

In 1950, Krabacher and Merchant[36] reported on work done at The Cincinnati Milling Machine Co. on the "Basic Factors in Hot-Machining of Metals". The influence of elevated temperature machining on basic metal cutting quantities, while turning and milling Inconel X, Timken 16-25-6, S-816 and AISI 3145 were examined. Studies of the mechanics of cutting at elevated temperatures were made in which chip friction, shear strength, and machining constant were measured. In addition, tool-chip interface temperatures were calculated. These data were correlated with data obtained from milling tool life tests on the same materials.

In 1954, Dr. M. Kronenberg[37] reported in an unpublished report on hot machining research done two years earlier at the R. K. LeBlond Machine Tool Company and International Harvester Company with the assistance of Tocco Company. He reported an almost 50% reduction in power requirements at 1400°F, excellent surface finish and a 16:1 increase in metal removal rate at 1200°F, when turning C1049 steel track rollers. Induction heating was used. The process was not used in production due to the costs of the extremely high heating power requirement on the technique used. It was recommended where other machining methods made a job otherwise impossible.

From 1952 through 1956, no significant investigation in the area of hot machining was reported in the literature or known to be carried out by any investigator.

However, in 1957, work in the area of elevated temperature machining was again initiated at The Cincinnati Milling Machine Co. following a survey of the aircraft industry which indicated the urgent need for assistance in the machining of high strength thermal resistant metals. This investigation was continued through 1958 to September 1959, when it was discontinued with the initiation of this Air Material Command Research Contract. Basic quantities of metal cutting including shear angle, shear strength at the shear plane, cutting forces, tool-chip interface temperatures, mean coefficient of friction, and machining efficiency were related to workpiece temperature for four materials, AISI 4340, Thermold J, 17-7 PH, and 17-4 MO. Milling life tests at elevated temperatures on these materials showed that caribde tools could be used at 300-500 fpm and 1000°F where at room temperature, only H.S.S. tools at 25 fpm could be used. These results are included in this report.

Since 1957, several companies have experimented with hot machining with results varying from excellent to complete failure. Some of the results from these experiments as reported in unpublished company reports are given below:

In April 1958, K. Loo[40] reported to North American Aviation, Inc. on the "Investigation of Drilling Thermal Resistant Materials at

Elevated Temperatures". The experiments in hot drilling showed up to 85% decrease in drill forces (thrust) and up to 10 times the tool life obtained at room temperature in drilling AM 355 CRES, VascoJet 1000, 4340 steel, 17-4 PH CRES, and Inconel X. A split point drill grind was used. Good surface finish was reported at elevated temperatures. Temperatures to 750°F were provided by radiant heat from three 1000 watt quartz lamps placed under the 9/16 inch thick workpiece. The workpiece holding vise had internal passages for water cooling.

Another report of North American Aviation, Inc. entitled, "Elevated Temperature Machining", indicates the results of hot machining on AM 355 CRES, PH 15-7 MO Cres, Rene' 41, H-11 alloy. Heating to temperatures of 1400°F was done with resistance heaters. An optimum temperature of 800°F for AM 355 CRES was established.

In a report entitled, "Elevated-Temperature Machining of AM355 Stainless Steel"[61] at Boeing Airplane Co., H. W. Smith investigated milling and drilling of AM355 up to 350°F. Drilling tests were conducted on a workpiece submerged in hot oil. Results showed a six-fold increase in tool life at 350°F. Milling tests showed lower tool life at 200°F and 350°F on a furnace heated workpiece than was obtained at room temperature.

Mr. J.F. Shea of Vought Aeronautics Division of Chance Vought Aircraft, Inc., mentioned in a letter results obtained at Chance Vought. Tool life was increased four times when slab milling M-252 at 800°F. Drilling tungsten at 600°F gave a seven-fold increase in drill life. Hand drilling of HS-25 was considerably easier at 1000°F.

In January 1960, H. Frommelt[22] of the Metal Removal Center of Spring Garden Institute reported on the machining of the excess weld material from railroad rails while they were still hot from the welding operation. The optimum temperature was determined to be 600°F where a 50% power reduction and three-fold increase in tool life were obtained. Mention is also made of successfully drilling Hastelloy at 350°F to 400°F.

SURVEY OF INDUSTRY (STATE OF THE PROBLEM)

To determine the state of the problem a survey of fourteen companies engaged in aerospace work was conducted. The results of this survey were used as a guide for the work on hot machining. The survey showed that over 30% of the total milling, drilling and turning operations are on high strength thermal resistant metals. The most important alloys included, martensitic low alloy steels, nickel base alloys, cobalt base alloys, and precipitation hardening stainless steels. An average of 40% of the operations performed on these materials are performed when they are hardened as high as 58 Rc (300 KPSI). The aerospace manufacturers predicted that the future (today) would require machining of tungsten alloys, molybdenum, columbium and more nickel and cobalt alloys. Prints of typical parts were offered and specific problems encountered were discussed.

Later on, prior to undertaking the various phases of elevated temperature machining investigation, visitations were again made to as many of the companies as possible, in order to keep abreast of their current and future usage of metals. As pointed out before, these surveys not only indicated the most important groups of metals being used, but also enabled us to discuss problems encountered in machining and to select typical parts from which we later chose the parts undertaken in our "Evaluation of Elevated Temperature Machining" report.

Correspondence, increasing efforts by investigators, and our discussions during the field surveys, all emphasized the great need for improved methods in the machining of refractory metals.

Our studies on the effect of elevated temperature on tool-chip interface temperatures and maximum tool forces in face milling refractory alloys, created a desire to further this investigation. This resulted in our undertaking to evaluate hot machining of four refractory metals and alloys as well as two titanium alloys.

OBJECTIVES OF THIS PROJECT

(1) Make a detailed evaluation of what is involved in the way of methods and techniques for elevating workpiece temperatures, and analyze heat distribution and flow in workpiece.

(2) Develop and evaluate heating techniques applicable to turning, milling and drilling operations on various classes of materials. The methods should provide a high degree of localization and concentration of heat to minimize distortion and thermal damage to the finished workpiece.

(3) Utilize these heating techniques in conducting tests to establish information on the machinability improvements that can be obtained by using hot machining.

(4) Conduct laboratory tests in milling, drilling and turning at room and various elevated workpiece temperatures. From these tests establish the relationships between the basic machining parameters.

(5) Evaluate test parts for the metallurgical effects of elevated temperature machining on the test materials.

(6) Utilize the experience and understanding developed in the earlier studies in the manufacture of aerospace parts of typical configurations using elevated temperature machining.

(7) Compare, by actual test, the cost and time required to produce the part by hot machining with that required with conventional practice.

WORK MATERIALS

The selection of the initial work materials for these hot machining evaluations was based largely on a survey of some 28 aircraft engineering companies carried out in 1956 by The Cincinnati Milling Machine Co. A part of that survey was aimed at finding out the types of difficult-to-machine-work materials which the aircraft industry would be using in the near future. Four materials considered representative of the types which would present problems in processing were selected to be used in the hot machining research studies which commenced at Cincinnati in 1957. It was thought desirable to preserve the continuity of this research work when this Air Force contract was awarded in September 1959, and review of the literature published in the interim in the area of aircraft materials, particularly the articles mentioned in the Bibliography, confirmed that the choice was still pertinent to the needs of the industry. It was, therefore, decided to continue with the same four materials.

In addition, the survey conducted in 1959 showed the necessity for including nickel and cobalt base alloys of which three were chosen. The increased interest in the machining of refractory metals led to the supplementary work and the selection of tungsten, molybdenum, tantalum, columbium, and titanium alloys.

These alloys, whose compositions are listed in Figure 1, are given below by groups.

A. Iron Base Alloys

(1) Republic Steel's low alloys martensitic steel, AISI 4340

(2) Universal Cyclops hot work die steel known as Thermold J or Unimach No. 2

(3) Armco Steel's precipitation hardening stainless steel, 17-7 PH

(4) Universal Cyclop's precipitation hardening stainless steel, Uniloy 17-4 MO, otherwise known as AM350

(5) Armco Steel's precipitation hardening stainless steel, PH 15-7 MO

B. Nickel Base Alloys

(1) General Electric's nickel base alloy Rene' 41

(2) International Nickel Co.'s nickel base alloy, Inconel X

C. Cobalt Base Alloy

(1) Union Carbide's cobalt base alloy Haynes Alloy No. 25

D. Titanium Base Alloys

(1) Crucible Steel's titanium alloy C120 AV also known as 6Al-4Va.

(2) Crucible Steel's titanium alloy B120VCA -- β titanium (13V-11Cr-3Al).

E. Refractory Alloys

(1) General Electric's 93% theoretical density, pressed and sintered unalloyed tungsten.

(2) Oregon Metallurgical Co.'s alloy 60% tungsten and 40% molybdenum

(3) Universal-Cyclops Steel's molybdenum alloy TZM

(4) Fansteel Metallurgical's tantalum alloy 90% Ta-10% W.

(5) Westinghouse's columbium (niobium) alloy B-33

(6) Fansteel Metallurgical Co.'s columbium (niobium) base alloy, Fansteel No. 82 also known as F.S. 82.

The workpieces were subjected to various heat treatments as recommended by the manufacturer. These heat treatments are shown in

Figures 2 through 9. The effect of temperature on the ultimate tensile strength, yield strength and ductility for the iron base alloys are shown in Figures 10, 11, 12. Similar curves for the nickel, cobalt, and titanium base alloys are given in Figures 13, 14 and 15 while the curves for the refractory alloys are given in Figures 16, 17 and 18. The data contained in these curves are typical data supplied by the manufacturers.

FIGURE 1

MATERIALS USED IN THIS PROJECT

Alloy	% Composition												
	Cr	Ni	Co	Mo	W	C	Mn	Si	Al	Fe	Ti	Other	Other	Other
AISI 4340	.8	1.8	-	.25	-	.43	-	-	-	96.7	-			
Thermold J	5.0	1.5	-	1.40	-	.50	.40	1.1	-	89.1	-		1.00V	
17-7 PH	17.0	7.0	-	-	-	.07	.65	.65	1.0	73.8	-			
17-4 MO	17.0	4.0	-	3.00	-	.10	-.	-	-	75.8	-		.15N	
PH 15-7 MO	15.0	7.13	-	2.50	-	.09	1.00	1.00	1.63	71.58	-	.04P	.03S	
Rene' 41	19.0	55.31	11.0	10.0	-	.09	-	-	1.5	-	3.1			
Inconel X	14.96	69.0	1.0	-	-	.08	1.0	0.5	1.0	8.0	2.75	.01S	.5Cu	1.2Cb
Haynes Alloy No. 25	20.0	10.0	49.4	-	15.0	.10	1.5	1.0	-	3.0	-			

90 Ta - 10 W	90 Ta 10 W
B-33 columbium	V 5.0, O .012, N .006, C .006, Cb remainder
TZM molybdenum	Ti 0.5, Zn .08, Traces C, O, H, N, Fe, Ni, Si, Mo remainder
Unalloyed tungsten	Mo 0.02, Traces Al, Ca, Si, Fe, Cr, Ni, Cu, Mn, Mg, Sn, Bal. W
C 120 AV titanium	Al 6.0, V 4.0, H .0038, N 0.02, Fe 0.19, Ti remainder
B 120 VCA titanium	V 13.0, Cr 11.0, Al 3.0, Fe 0.27, H 2.0160, N .03, W 0.02, Mo .09, Ti remainder
Fansteel No. 82	Cb (Nb) 66.25, Ta 33.0, ZR .75
60% W 40% MO	W 60, Mo 40.

AISI 4340 (Martensitic Low Alloy Steel)

Republic Steel Corp.

Heat Treatment Procedure

Oil Quenched and Air Cooled

(1) Heat to 1600° - 1650°F
(2) Hold for 2 hours
(3) Cool to 1225°F
(4) Equalize at 1225°F
(5) Transform at 1225°F for a minimum of 8 hours
(6) Cool in furnace to 1150°F
(7) Remove and air cool (annealing operations)

---

(8) Heat to 1500° - 1575°F
(9) Quench in oil
(10) Air cool
(11) Draw at 375° - 400°F immediately for 2 hours minimum
(12) Average hardness obtained - 530 BHN

Anneal as above, items 1 through 7, draw 775°F

(8) Heat to 1525° - 1550°F
(9) Quench in oil
(10) Air cool
(11) Draw at 775° immediately for 2 hours minimum
(12) Hardness 44 Rc, 415 BHN

Anneal as above, items 1 through 7, draw 1000°F

(8) Heat to 1500° - 1575°F
(9) Quench in oil
(10) Cool to room temperature
(11) Draw to required hardness in range of 900° - 1025°F
(12) Average hardness obtained - 390 BHN

FIGURE 2

THERMOLD J (Hot Work Die Steel)
(Other Name) UNIMACH No. 2

Universal-Cyclops Steel Corp.

Heat Treatment Procedure

Double Tempered at 800°F

(1) Preheat to 1200°F
(2) Increase to 1825°F
(3) Air quench
(4) Double temperature to 800°F
(5) Average hardness obtained - 570 BHN

Double Tempered at 1100°F

(1) Preheat to 1200°F
(2) Increase to 1875°F
(3) Air quench
(4) Double temperature to 1100°F
(5) Average hardness obtained - 390 BHN

FIGURE 3

17-7 PH (Precipitation Hardening Stainless Steel)

Armco Steel Corporation

Heat Treatment Procedure

Heat Treat Designation - TH 1050

(1) Heat to 1800°-1850°F
(2) Quench rapidly in water (annealing operation)

---

(3) Heat to 1400°F ($\pm$ 25°) for 1-1/2 hours
(4) Cool to 60°F ($\pm$ 10°) within 1 hour
(5) Harden at 1050°F ($\pm$ 10°) for 1-1/2 hours
(6) Air cool
(7) Average hardness obtained - 390 BHN

Heat Treat Designation - Reheating TH 1050

(1) Heat to 1800°-1850°F
(2) Quench rapidly in water (annealing operation)

---

(3) Heat to 1400°F ($\pm$ 25°) for 1-1/2 hours
(4) Cool to 60°F ($\pm$ 10°) within 1 hour
(5) Harden at 1050°F ($\pm$ 10°) for 1-1/2 hours
(6) Air cool (TH 1050)

---

(7) Heat to 1075°F ($\pm$ 10°) for 1-1/2 hours
(8) Air cool
(9) Heat to 1100°F for 1-1/2 hours
(10) Air cool
(11) Average hardness obtained - 360 BHN

FIGURE 4

UNILOY 17-4 MO (Precipitation Hardening Stainless Steel)

Universal Cyclops Steel Corp.

Heat Treatment Procedure

Double Ageing Treatment

(1) Heat to 1750°-1850°F
(2) Cool rapidly (annealing operation)

---

(3) Heat to 1350°F for 1 hour
(4) Air cool
(5) Reheat to 950°F for 4 hours
(6) Air cool
(7) Average hardness obtained - 360 BHN

Sub-Zero Treatment

(1) Heat to 1750° - 1950°F
(2) Cool rapidly (annealing operation)

---

(3) Chill to -100°F for 2 hours
(4) Heat to 950°F for 4 hours
(5) Air cool
(6) Average hardness obtained - 380 BHN

FIGURE 5

PH 15-7 MO (Precipitation Hardening Stainless Steel)

Armco Steel Corporation

Heat Treatment Procedure

Solution Treatment

(1) Heat to 1950°
(2) Hold 3 minutes for every .1 of thickness
(3) Air Cool (annealing operation 160-180 BHN)

FIGURE 6

Rene' 41 (nickel base alloy)

General Electric Company

<u>Heat Treatment Procedure</u>

(1) **Solution treat at 1950°F for 4 hours**

(2) **Air cool**

(3) **Age at 1400°F for 16 hours**

(4) **Air cool**

(5) **Hardness 40-41 Rc 372-382 BHN**

FIGURE 7

Inconel X (nickel base alloy)

International Nickel Company

Heat Treatment Procedure

(1) Heat to 2100°F for 2 to 4 hours

(2) Air cool (solution treatment)

(3) 1500°F for 24 hours

(4) Air cool (high temperature ageing)

(5) 1300°F for 20 hours

(6) Air cool (low temperature ageing)

(7) Hardness 26-37 Rc 262-340 BHN

FIGURE 8

HAYNES ALLOY NO. 25 (COBALT BASE ALLOY)

UNION CARBIDE COMPANY

Heat Treatment Procedure

(1) Solution Treat

(2) Heat to 2250-2265°F ($\pm$ 25°F)

(3) Soak 75 to 105 minutes (for .751 to 1.375 thickness)

(4) Water Quench

(5) Hardness 24-25 Rc   250-255 BHN

FIGURE 9

EFFECT OF TEMPERATURE ON THE ULTIMATE TENSILE STRENGTH OF VARIOUS STEELS

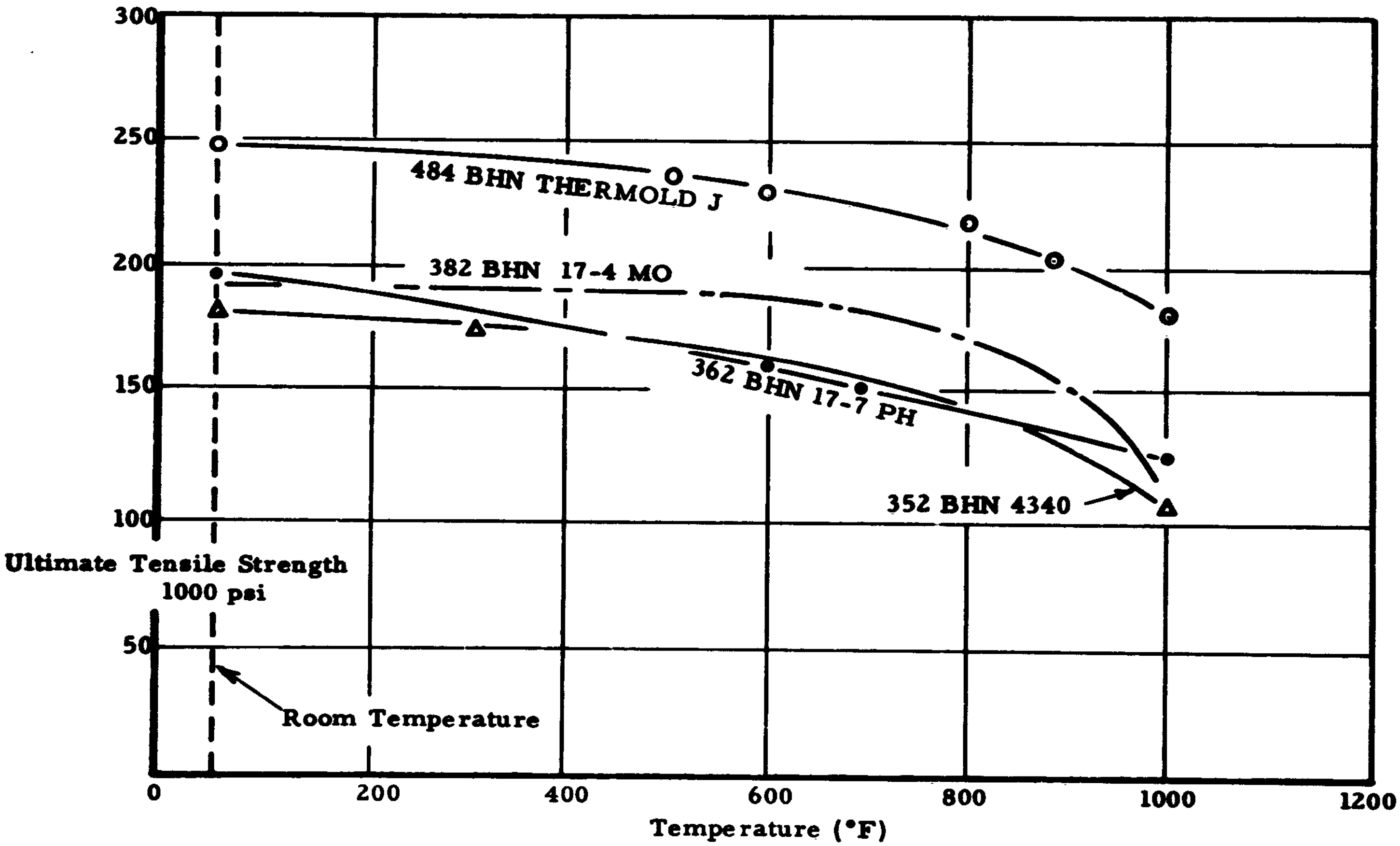


FIGURE 10

EFFECT OF TEMPERATURE ON THE YIELD STRENGTH OF VARIOUS STEELS

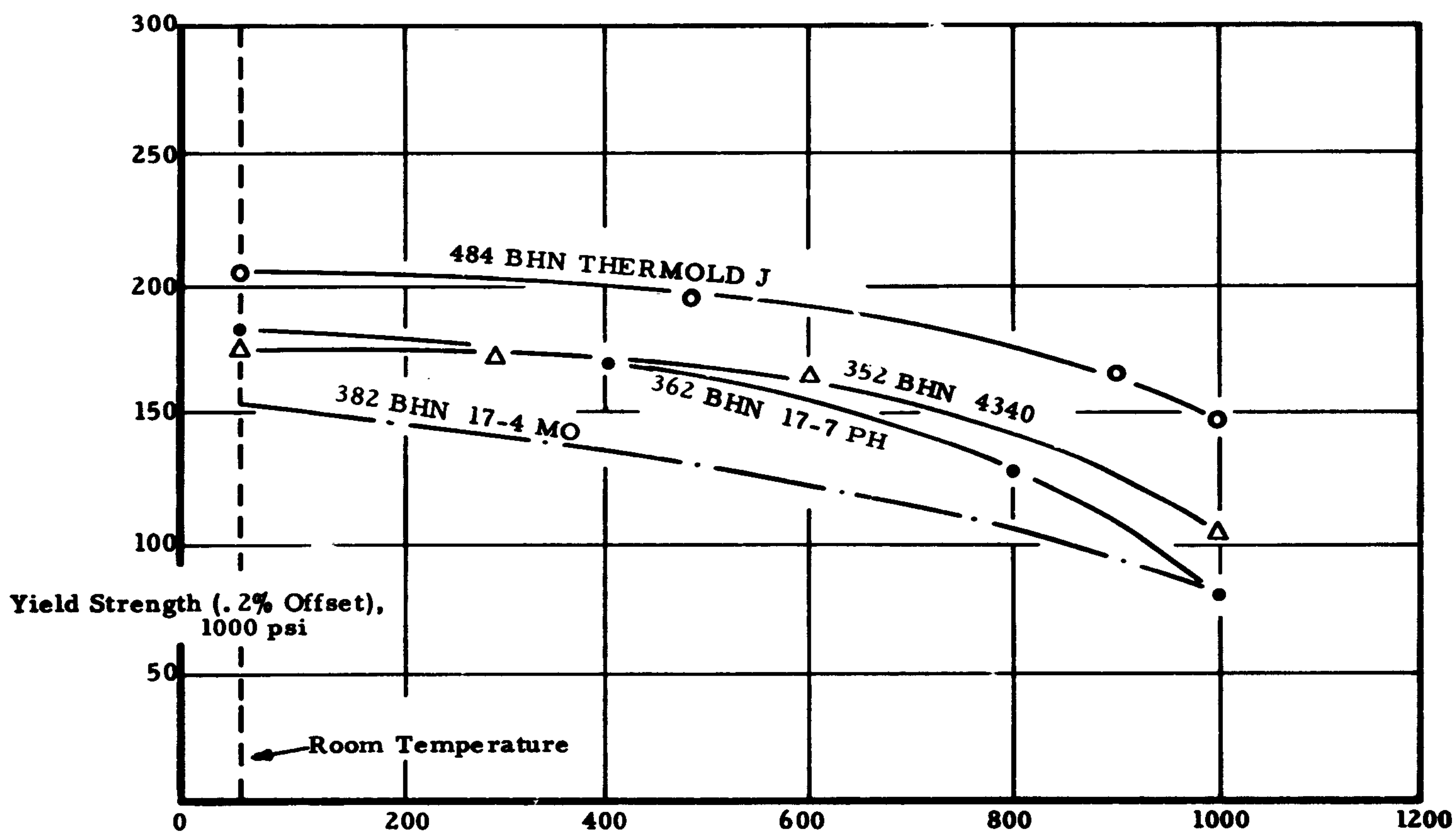


FIGURE 11

EFFECT OF TEMPERATURE ON THE DUCTILITY
OF VARIOUS STEELS

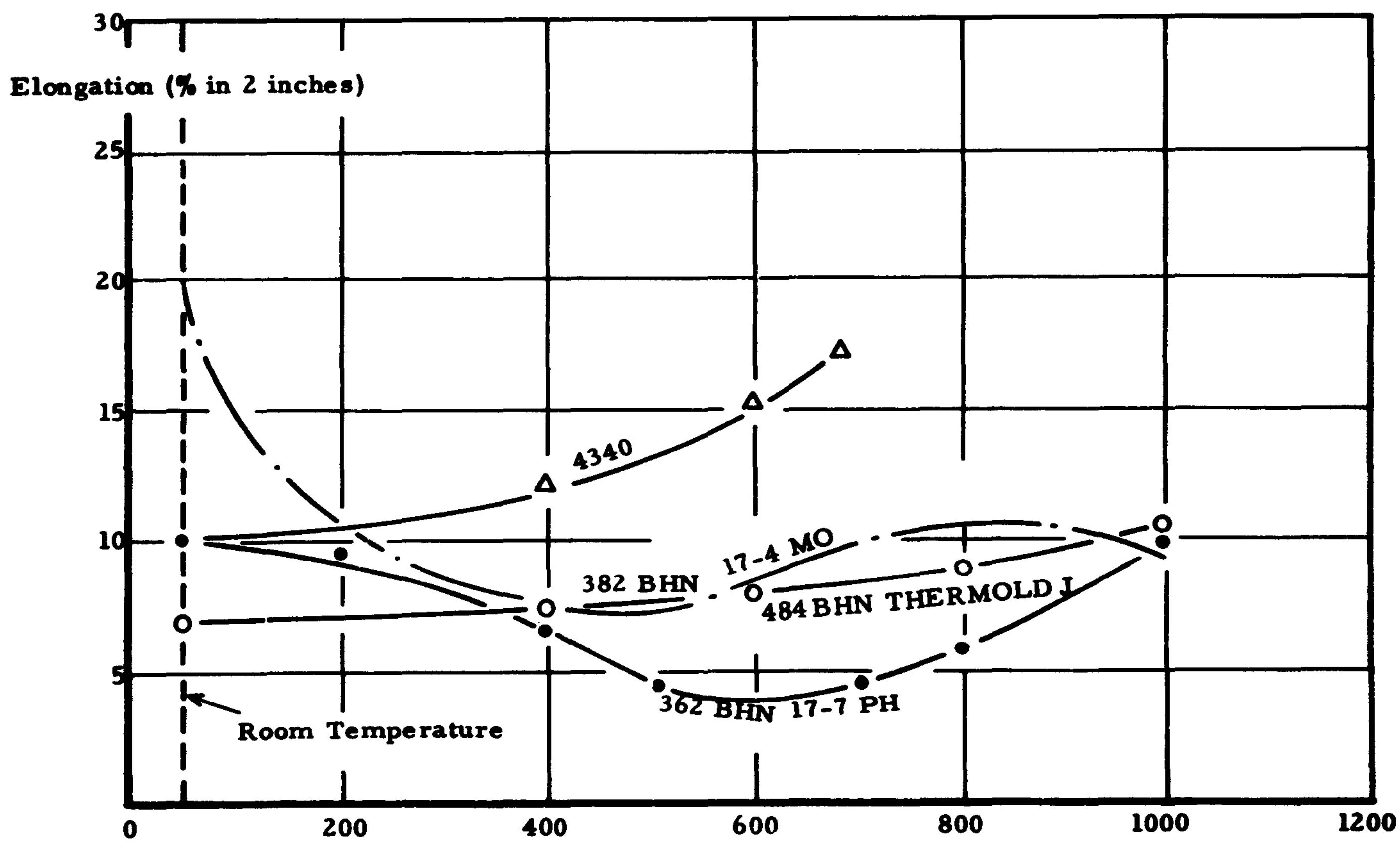


FIGURE 12

EFFECT OF TEMPERATURE ON TENSILE STRENGTH

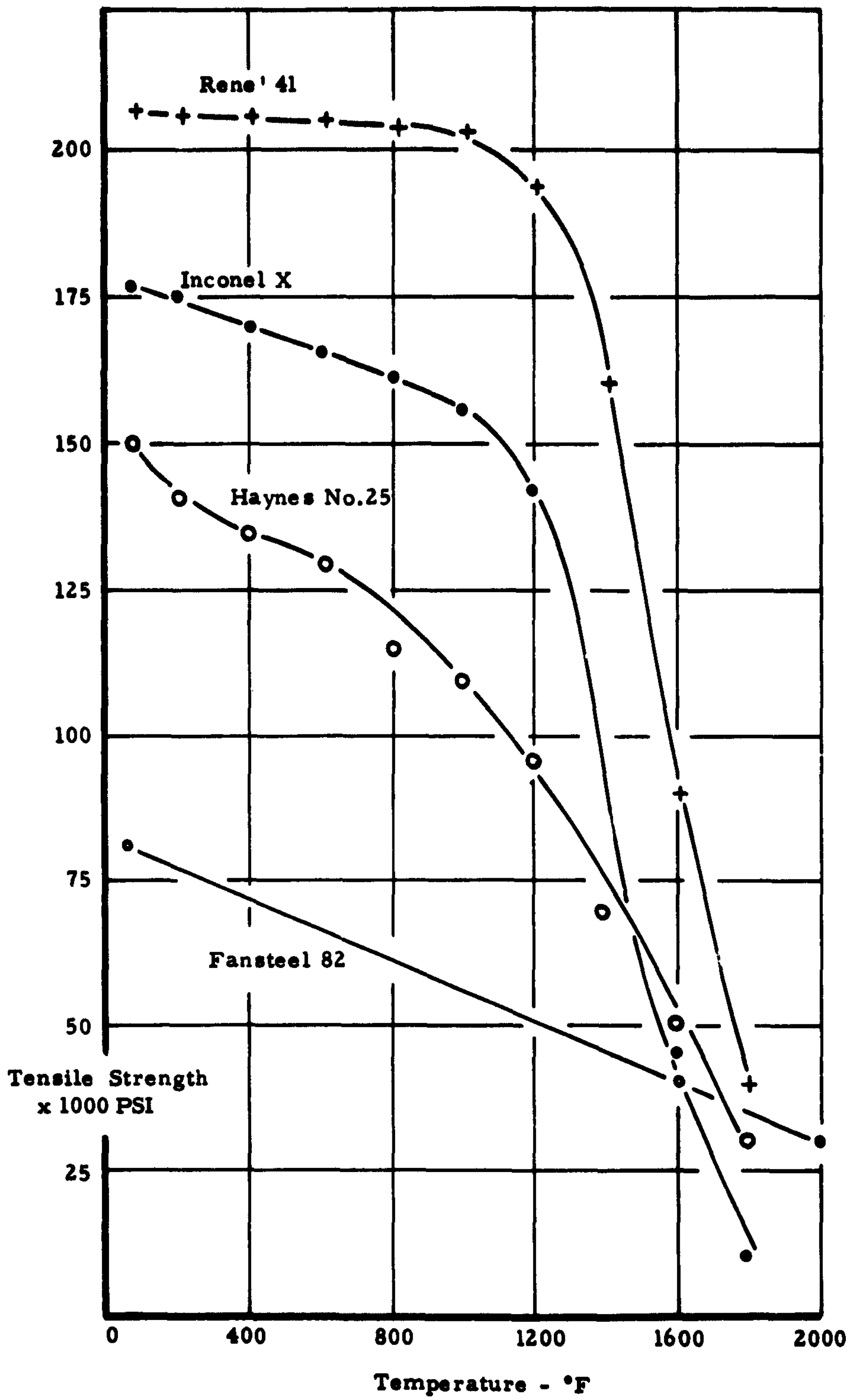


FIGURE 13

EFFECT OF TEMPERATURE ON YIELD STRENGTH

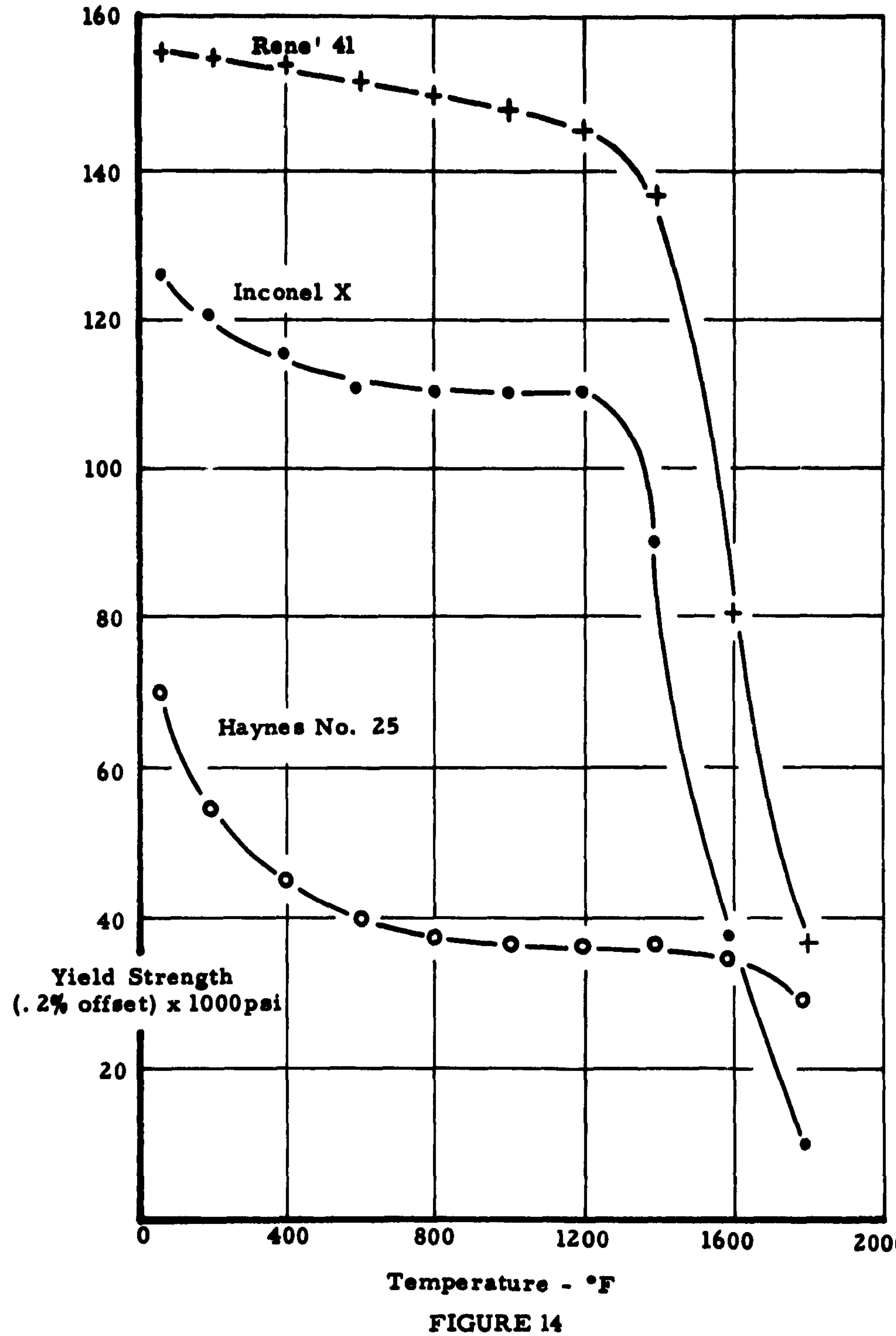


FIGURE 14

EFFECT OF TEMPERATURE ON DUCTILITY

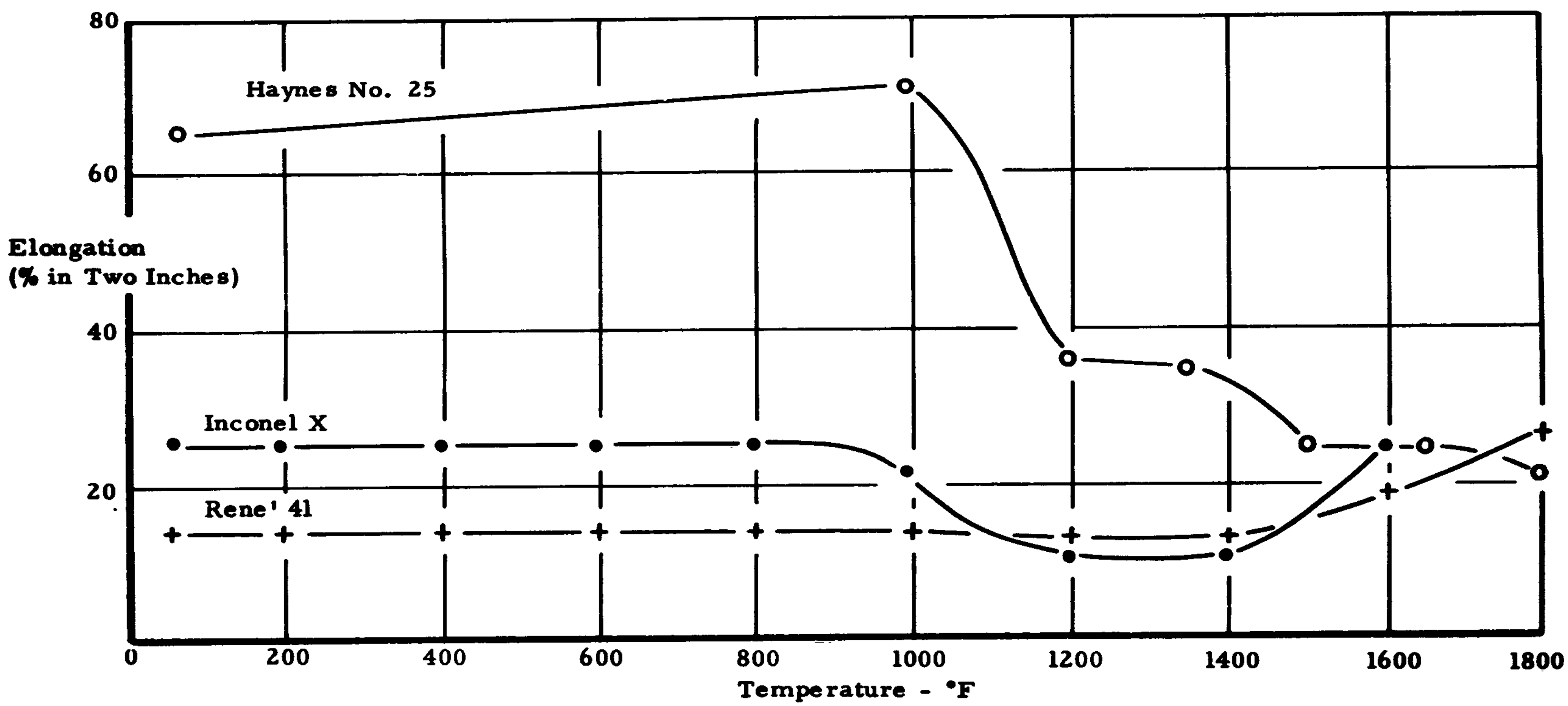


FIGURE 15

EFFECT OF TEMPERATURE ON ULTIMATE TENSILE STRENGTH OF VARIOUS REFRACTORY METALS

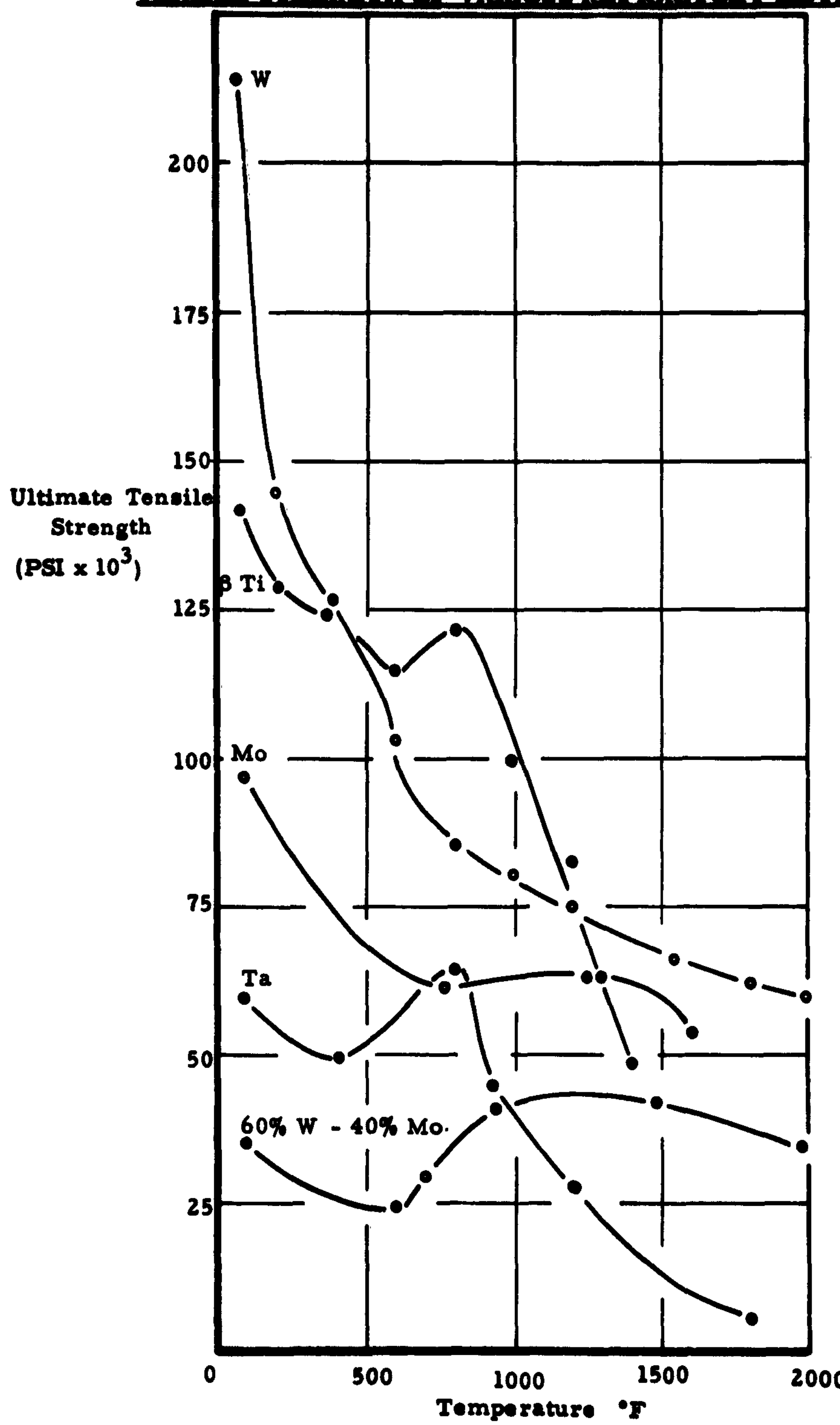


FIGURE 16

EFFECT OF TEMPERATURE ON YIELD STRENGTH OF REFRACTORY METALS

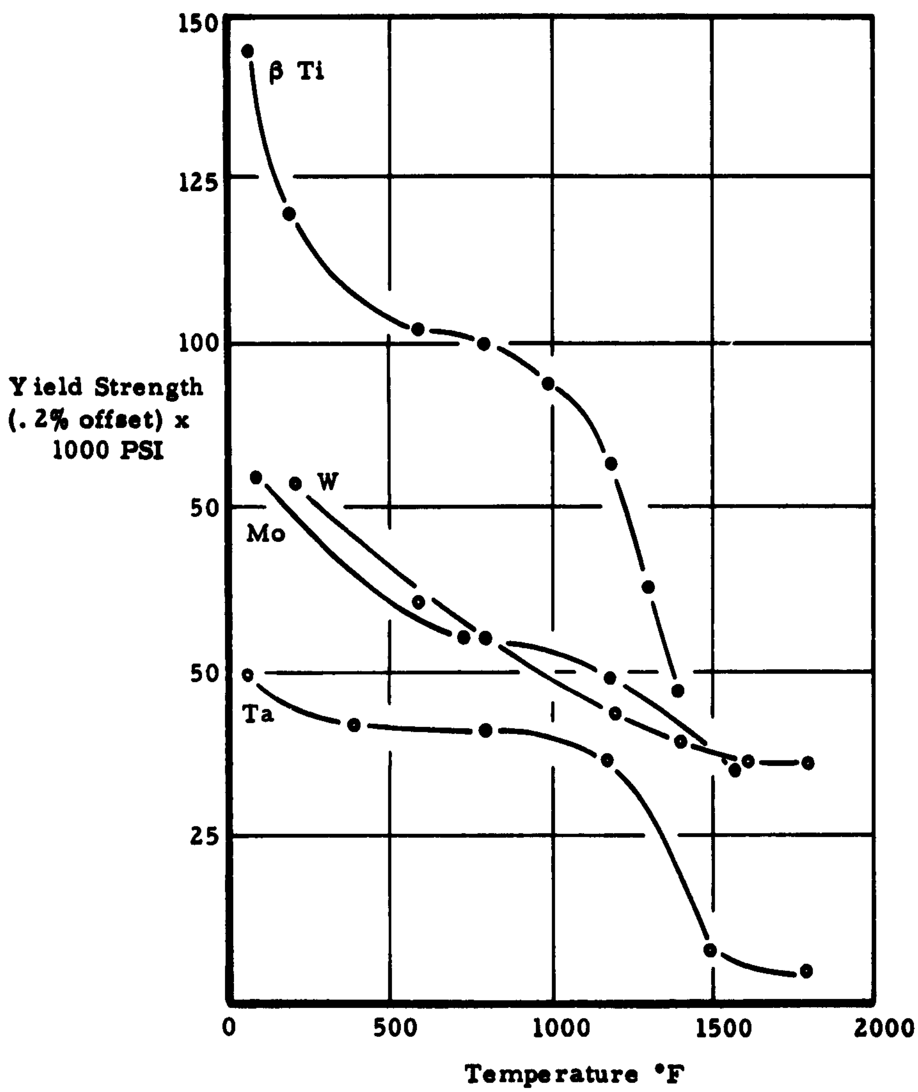


FIGURE 17

EFFECT OF TEMPERATURE ON DUCTILITY OF REFRACTORY METALS

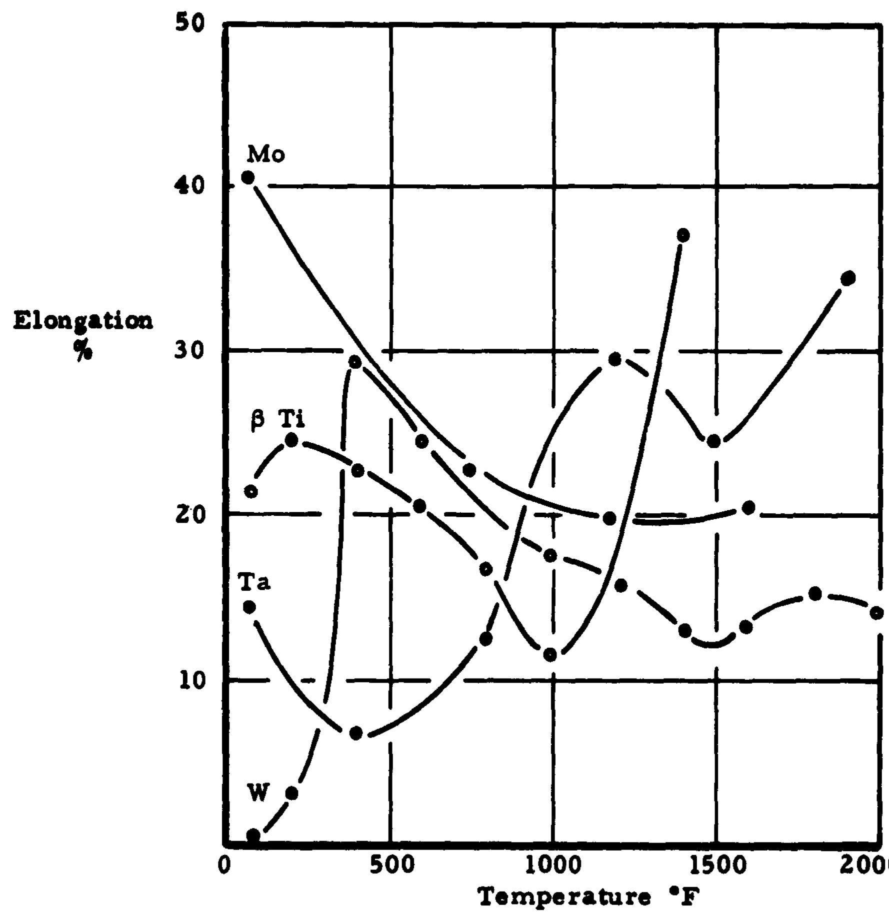


FIGURE 18

EXPERIMENTAL MACHINING STUDIES

Objectives

Obtain machinability data, cutting speed tool life relationships, determine the advantages and disadvantages of elevated temperature machining in turning, milling and drilling, and determine techniques suitable for its application in production.

ORTHOGONAL TURNING TESTS

Objectives

Determine how the basic parameters involved in metal cutting are affected by introducing workpiece temperature as a variable. By using an orthogonal turning arrangement and physically measuring such quantities as tool forces, ratio of feed per revolution to chip thickness, and tool geometry, derive other fundamental quantities such as shear plane angle, mean coefficient of friction between tool and chip, and energy distributions in the process using the Merchant theory expounded in his "Mechanics of the Metal Cutting Process". Measure workpiece temperature and mean temperature at the chip-tool interface to obtain the correlation of these to the other basic parameters.

Apparatus

The equipment used for this purpose is shown, photographed, in Figure 19. It consisted of a 2 M. H. horizontal milling machine with a chuck holding the 2-1/8" diameter, 0.250" thick wall, tubular workpiece. The toolpost was mounted on the table of the machine. The arrangement was for orthogonal turning with only a two-dimensional tool force system involved.

The tool itself was held in a force dynamometer designed so that the tool was supported by a cantilever beam having strain gages affixed to it, these being wired in a wheatstone bridge circuit connected to an amplifier-recorder. The application of force at the tool strains the beam and gages, which results in alteration of the electrical resistance balance of the bridge. The change of signal is recorded. Suitable calibration of the apparatus before tests enables direct reading of the two components of the resultant tool force. To the right side of the picture (Figure 19) can be seen the cylinders of oxygen and propane gas which were used, via the multi-tip, water-cooled burner, to heat the workpieces. Pressure valves and a rapid gas shut-off cock were incorporated in the system for better control of the heating. Workpiece temperature was measured by shutting off the gas flow to the burner and using a contact pyrometer on the end of the tube. Tool, dynamometer and machine were insulated from flame splash, heat conduction, and radiation, by the use of asbestos board sheets.

Tool-Work Thermocouple

The mean temperature at the interface between tool, chip, and workpiece, was measured by using this interface as the hot junction of a thermocouple circuit, where, the thermo-electric members of the thermocouple were, of course, the sintered carbide tool material and the workpiece steel. The main errors in this type of tool temperature measuring system in the past have been due to parasitic e.m.f.'s arising at secondary junctions in the circuit. An attempt was made to overcome this by using a compensating circuit of the type described by Trigger, Campbell and Chao [67].

A schematic diagram is shown in Figure 20, where the workpiece has screwed into it a long shaft of the same material which passes through the hollow spindle of the machine and completes one-half of the electrical circuit through a simple mercury pot "slip ring" to the stationary amplifier recorder. The other half of the circuit is from the workpiece through the 1/2" square, 1/8" thick, "throwaway" carbide tool, via the error compensating circuit to the voltage measuring equipment. The compensating circuit was necessary since the small tool bit could have its temperature increased several hundred Fahrenheit degrees during cutting, thus generating thermo-electricity with the wire completing the circuit.

The principle of the compensating circuit is simply one of selecting two wire materials which will generate opposite polarity e.m.f.'s when heated in contact with the tool material being used. (Iron and Constantan were found to be most suitable for use with the cemented carbide tools used in these tests.) By measuring the ratio of these opposite polarity e.m.f.'s and incorporating resistances into each leg of the circuit, as shown, in the same ratio of magnitude, the IR drops in each leg of the circuit equate, and the parasitic e.m.f. is effectively nullified.

All of the cuts were taken at 250 fpm cutting speed and 0.0048 i.p.r. feed unless otherwise stated.

Results

The results obtained in these orthogonal turning hot machining tests are shown graphically in Figures 21 through 30.

The tool-work thermocouple was calibrated by immersing a piece of carbide tool and a chip from the workpiece in a bath of molten silver. The output of the tool work thermocouple was compared to the temperature of the bath as determined simultaneously by a standard thermocouple pair.

(a) Tool Forces: Consideration of Figure 21 shows that a 1000°F rise in workpiece temperature will give reductions of 40% to 50% in cutting force (F_c) and reductions of 33% to 66% in thrust force (F_t) at the tool.

It is interesting to note that workpieces of initial hardness approximately 400 BHN and 600 BHN, when heated by 1000°F, would cut with only a few percent difference in tool forces -- their elevated temperature strengths being much closer than the strengths at room temperature.

(b) Tool Temperatures: By referring to Figure 22, the effect of raising workpiece temperature upon the mean tool-chip interface temperature can be found. It appears that there are significant quantitative differences in this effect with different tool-workpiece material combinations as shown here:

Workpiece Material	F° Rise in Tool Temperature	F° Rise in Workpiece Temperature
Thermold J	250-350	1000
AISI 4340	700-1000	1000
17-7 PH	300-700	1000
17-4 MO	600-1100	1000

(c) Friction Between Chip and Tool and Shear Plane Angle: Making use of the Merchant analysis of the mechanics of chip formation, where:

F_c = Cutting force: force component acting in direction of motion of tool relative to workpiece

F_t = Thrust force: force component acting in a direction perpendicular to F_c and to the cutting edge

μ = Mean coefficient of friction acting between sliding chip and tool face

τ = Friction angle = arc tan μ

ϕ = Angle of the shear plane ahead of the tool

t_1 = Thickness of "chip" before removal = feed per revolution

t_2 = Thickness of chip

r_c = Cutting ratio = t_1/t_2

α = Rake angle of tool as measured in a plane perpendicular to its cutting edge.

It can be shown that,

$$\tan \phi = \frac{r_c \cos \alpha}{1 - r_c \sin \alpha}$$

defines the shear angle relationship from the quantities measured and

$$\mu = \frac{F_t + F_c \tan \alpha}{F_c - F_t \tan \alpha}$$

gives the mean friction coefficient from the quantities measured.

Again, as shown in Figure 23, each tool-workpiece pair must be considered in its own right. It would seem that with Thermold J die steel and 17-4 MO stainless steel, the mean coefficient of friction between chip and tool remains constant with work temperature increased up to 1000°F. However, AISI 4340 steel and 17-7 PH stainless steel show that friction in metal cutting may either increase or decrease with increased workpiece temperature.

The example of 390 BHN 17-7 PH being cut using Carboloy 370 carbide is what one might normally expect to occur in hot machining. As shown in Figure 24, the friction angle (τ) (and therefore the friction between chip and tool) increases with increasing workpiece temperature and the net result is to decrease the shear plane angle (ϕ) correspondingly.

Generally speaking, it appears from Figure 25 that the angle of the shear plane in chip formation remains fairly constant with increasing workpiece temperature for AISI 4340 steel and Thermold J, but decreases by amounts from 4° to 30° for the two stainless steels evaluated.

(d) Shear Strength at Shear Plane: The fundamental idea behind elevated machining is that at higher workpiece temperatures, the shear strength of the material is reduced and chip formation by plastic deformation due to shear on the plane ahead of the tool becomes easier. That this is so, is apparent from Figure 26 which shows reductions in the calculated mean shear stress on the plane of shear in the tests of the order of 40% to 60% with workpiece temperatures increased by 1000°F. These stresses may be taken as the apparent shear strength of the material during cutting since shearing is occurring. The values are arrived at by using the formula:

$$S_s = \frac{F_c \sin\phi \cos\phi - F_t \sin^2\phi}{A_o}$$

where

S_s = mean shear stress on plane of shear

F_c = cutting force

F_t = thrust force

ϕ = angle of shear plane

A_o = cross sectional area of "chip" before removal

An example of the effect of workpiece temperature on the shear strength-compressive stress relationship at the shear plane in metal cutting is shown in Figure 27 for 17-7 PH stainless steel. All points were obtained under the same cutting conditions, the only variable being workpiece temperature, and it can be clearly seen that both shear and compressive stresses at the shear plane are significantly reduced with increasing temperature.

(e) Chip Formation: That plastic deformation in cutting is assisted by elevating workpiece temperature is illustrated well by Figure 28 which shows photographs of cross sections of chips taken along their lengths. At 1300°F and 1500°F workpiece temperatures, it can be seen that the chip has been formed by a steady plastic flow of the work material and that the lower the temperature gets the less plastic the deformation becomes. At 300°F, the AISI 4340 chip is seen to be almost segmented and to have been formed with a series of discontinuities along its length, through half the thickness of the chip.

(f) Efficiency of Metal Removal: Defining the efficiency of metal removal as the cubic inches removed per horsepower-minute, an example of how this efficiency is increased by 40% to 50% for a 1000°F increase in workpiece temperature when cutting 390 BHN AISI 4340 steel is shown in Figure 29.

(g) Work Done in Chip Formation: By developing the theory of the mechanics of cutting further[43], it is possible to calculate the amounts of work done in shearing the metal and overcoming friction in cutting. The equations used are:

$$W_s = S_s\,[\cot\phi + \tan(\phi - \alpha)]$$

where

W_s = the amount of work done (ins. lbs per cubic ins.) in shearing the metal

$$W_f = \frac{\sin \phi \, (F_t \cos \alpha + F_c \sin \alpha)}{A_o \cos (\phi - \alpha)}$$

where

W_f = the amount of work done (ins. lb/cubic ins.) in overcoming friction

$$W_c = \frac{F_c}{A_o}$$

where

W_c = total amount of work done in cutting the metal.

Figure 30 shows an example of how these quantities of work done are reduced 30% to 50% by elevating a 390 BHN Thermold J die steel workpiece through 1000°F.

ORTHOGONAL TURNING APPARATUS

Flame Heating Set-Up with Tool Force and Tool Temperature Recorders

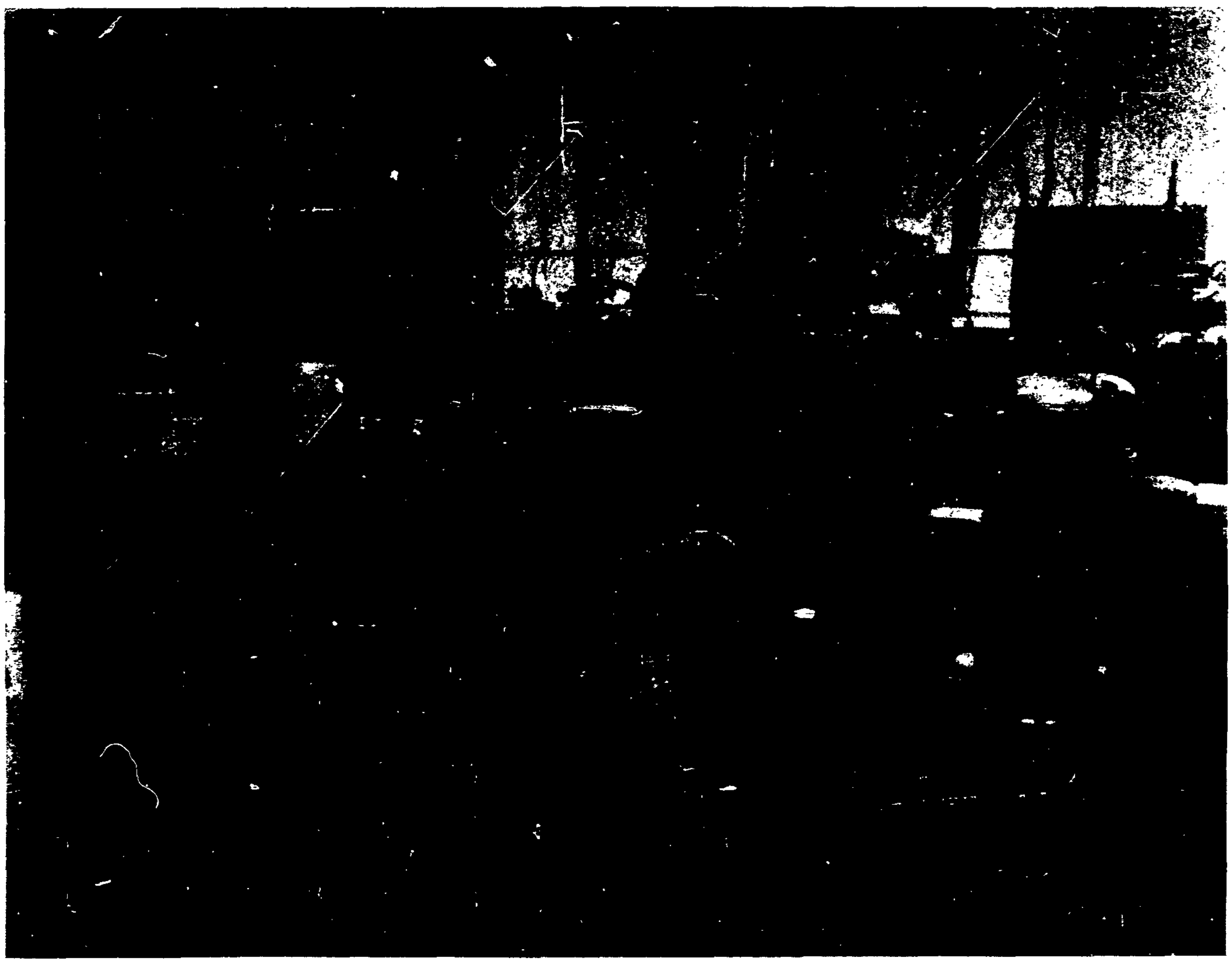
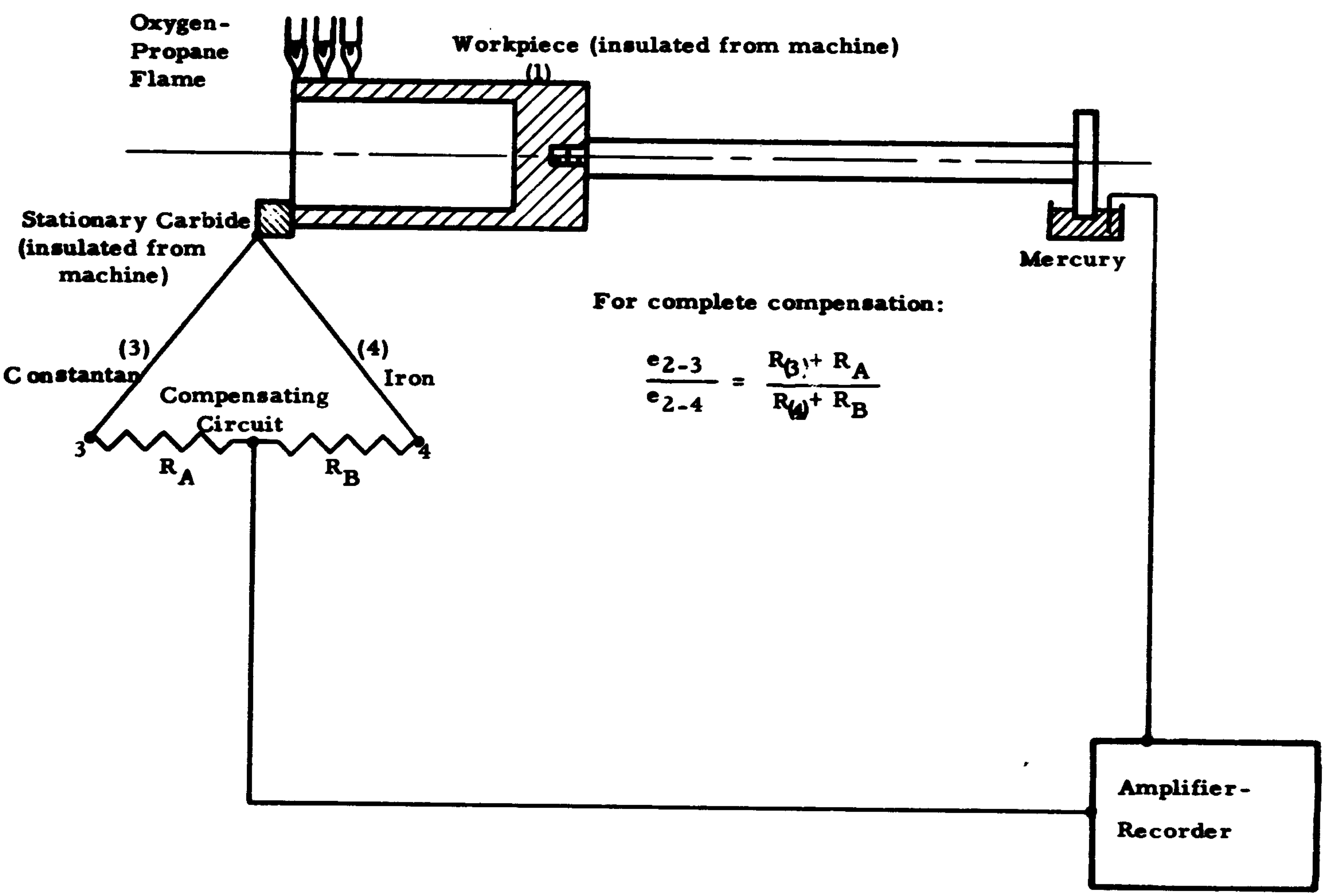


FIGURE 19

COMPENSATED TOOL-WORK THERMOCOUPLE CIRCUIT
(FLAME HEATED SET-UP)



$$\frac{e_{2-3}}{e_{2-4}} = \frac{R_{(3)} + R_A}{R_{(4)} + R_B}$$

FIGURE 20

EFFECT OF WORKPIECE TEMPERATURE ON TOOL FORCES

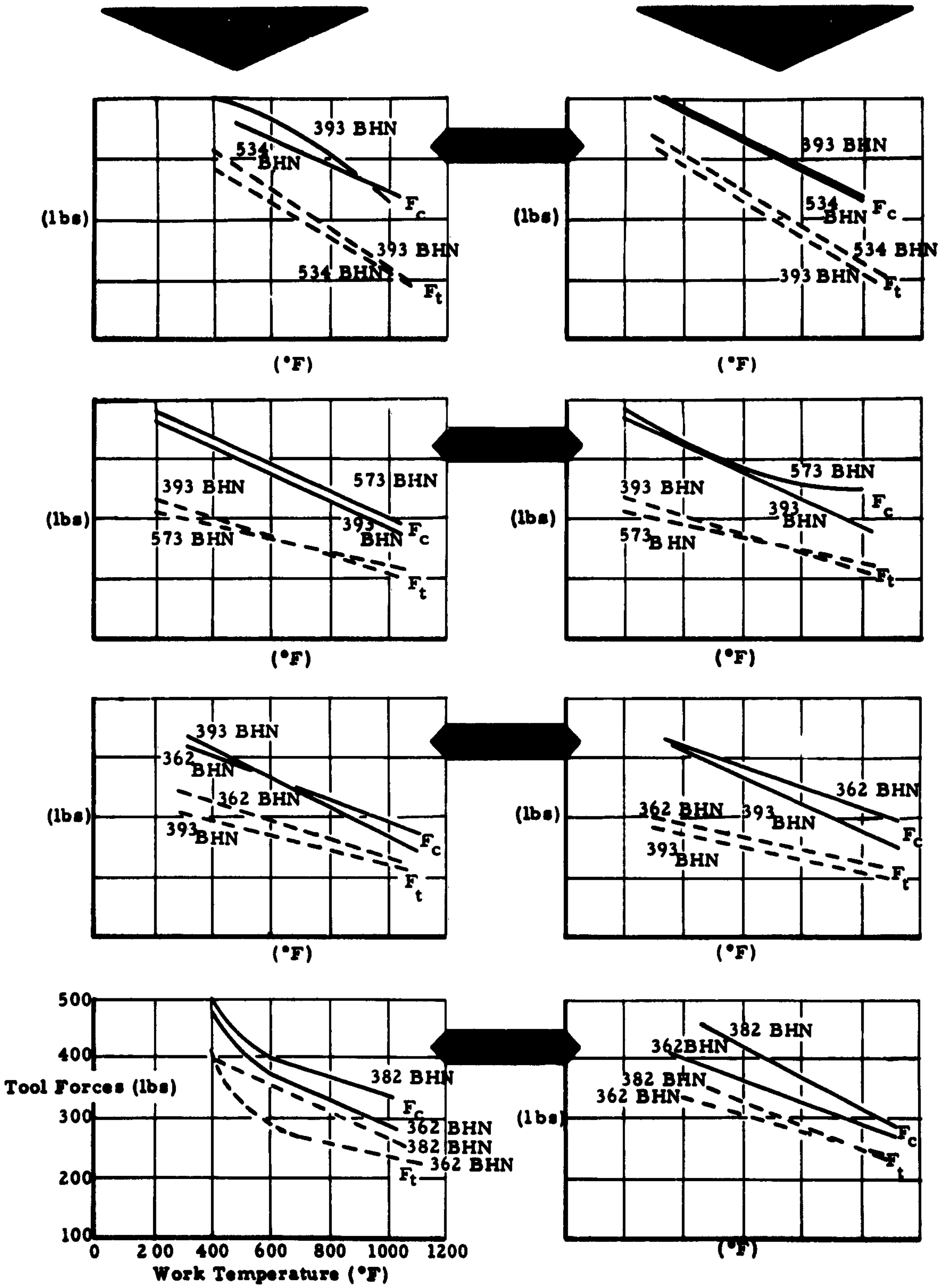


FIGURE 21

EFFECT OF WORKPIECE TEMPERATURE ON INTERFACE TEMPERATURE

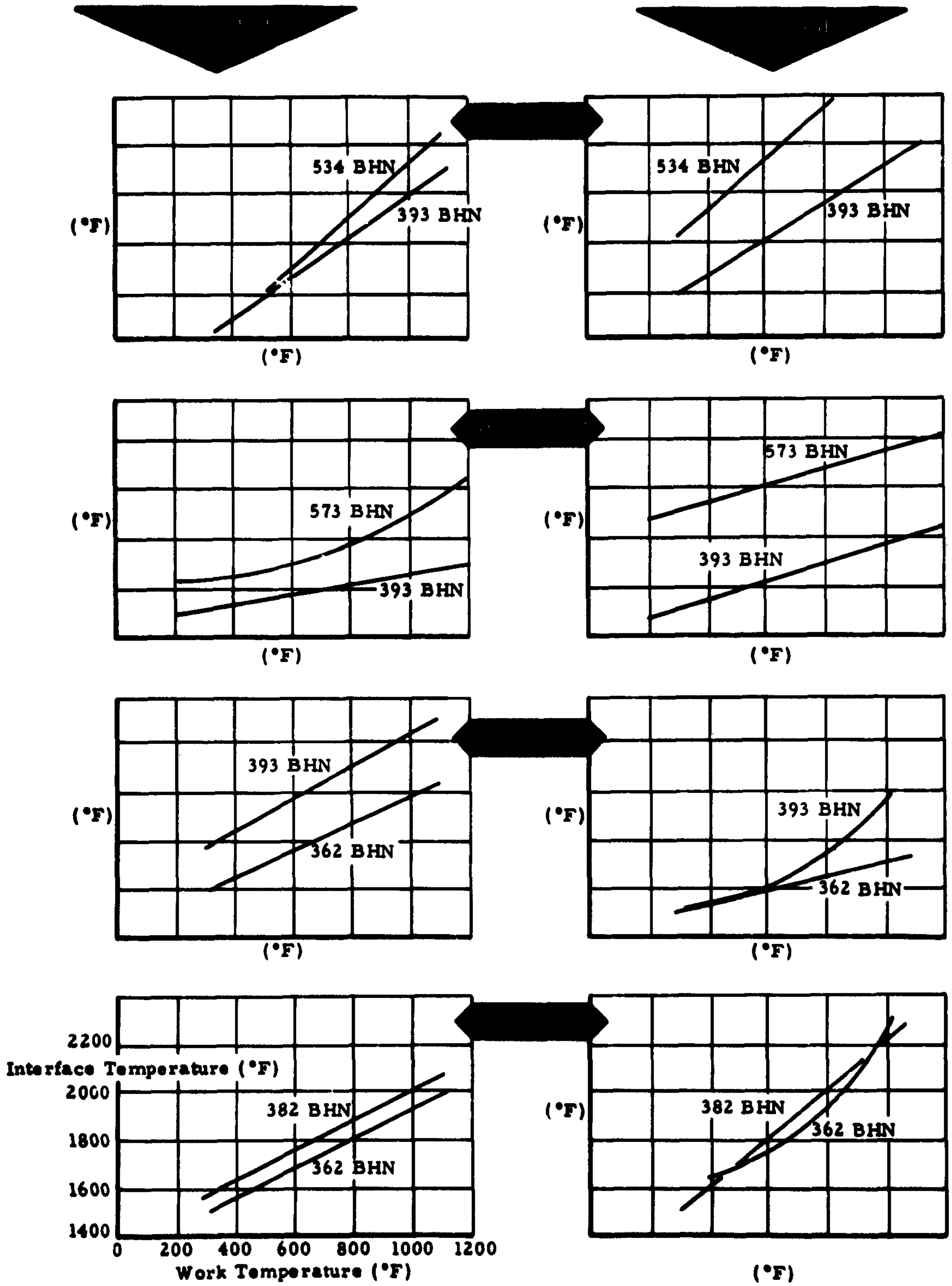


FIGURE 22

EFFECT OF WORKPIECE TEMPERATURE ON FRICTION COEFFICIENT

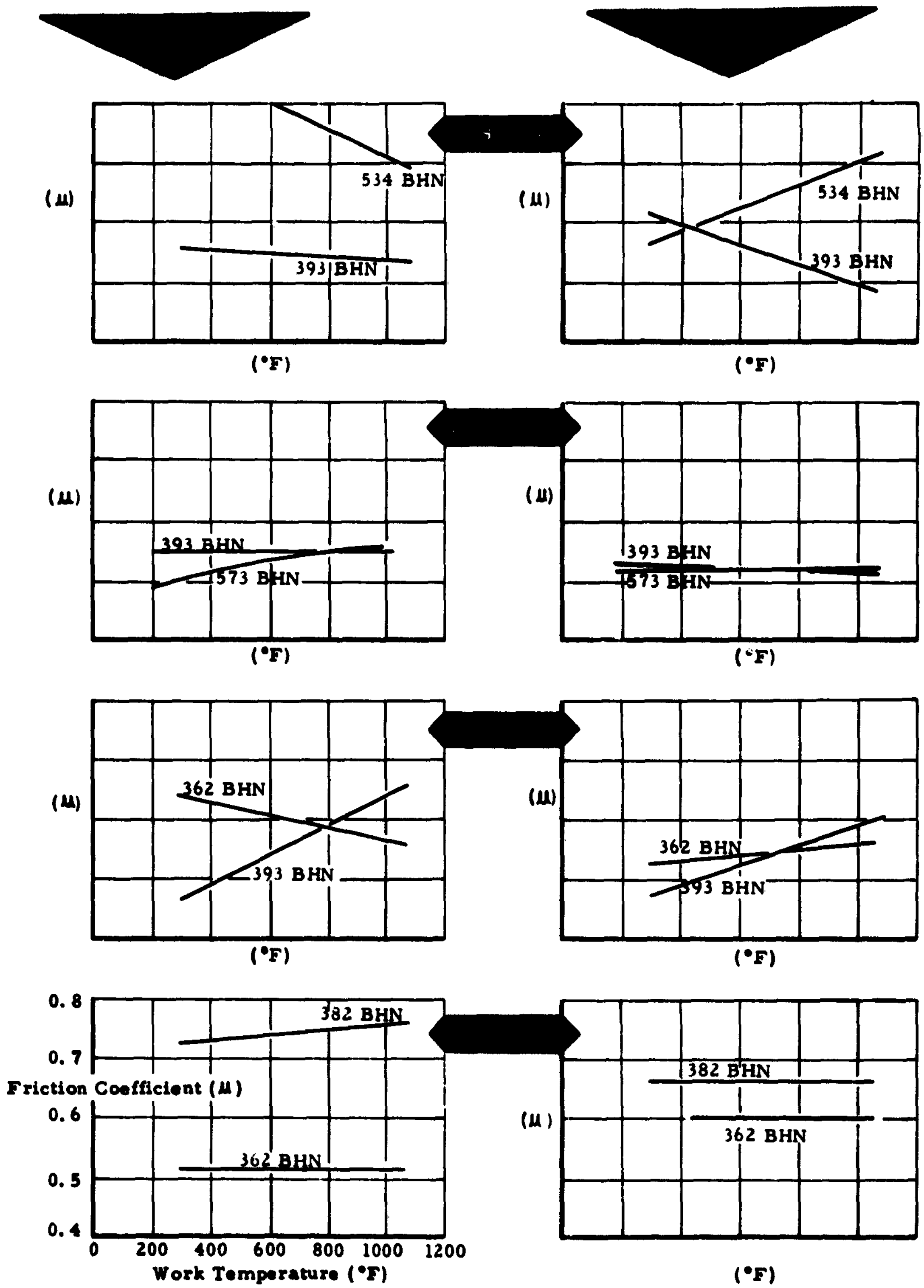


FIGURE 23

SHEAR ANGLE-FRICTION ANGLE RELATIONSHIPS
WHEN VARYING WORKPIECE TEMPERATURE

EACH POINT IS MARKED WITH THE CORRESPONDING WORKPIECE TEMPERATURE

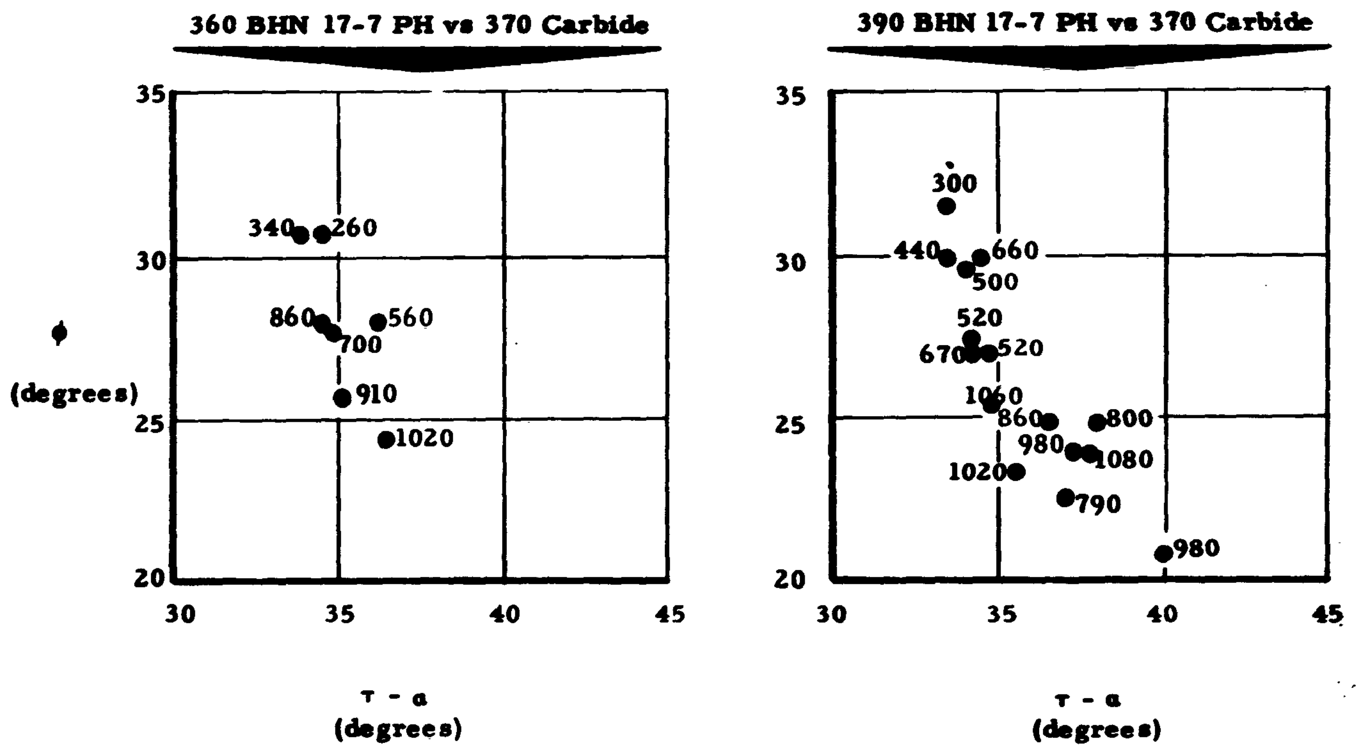


FIGURE 24

EFFECT OF WORKPIECE TEMPERATURE ON SHEAR ANGLE ϕ

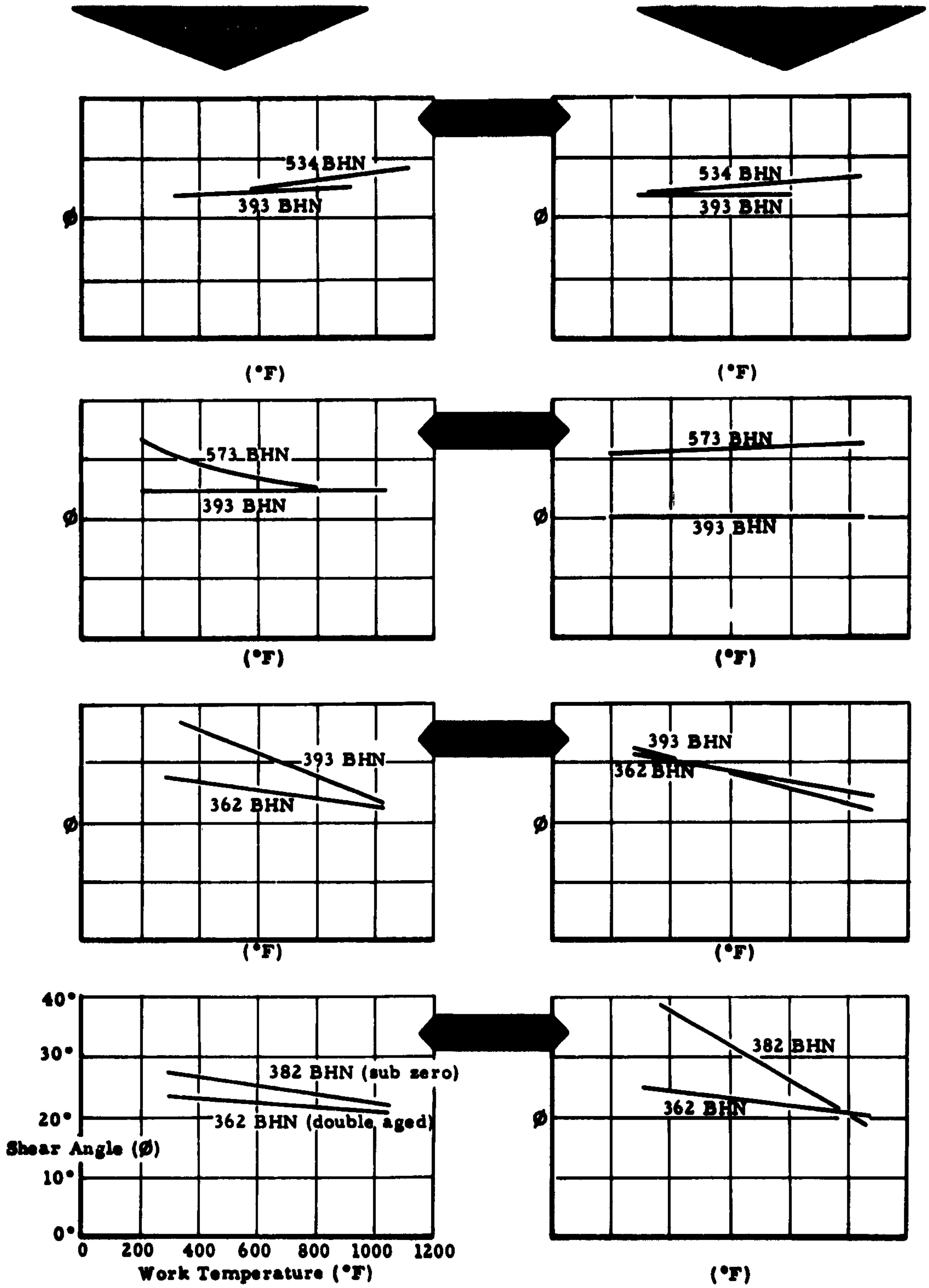


FIGURE 25

EFFECT OF WORKPIECE TEMPERATURE ON SHEAR STRENGTH

Shear Strength as Calculated at the Shear Plane

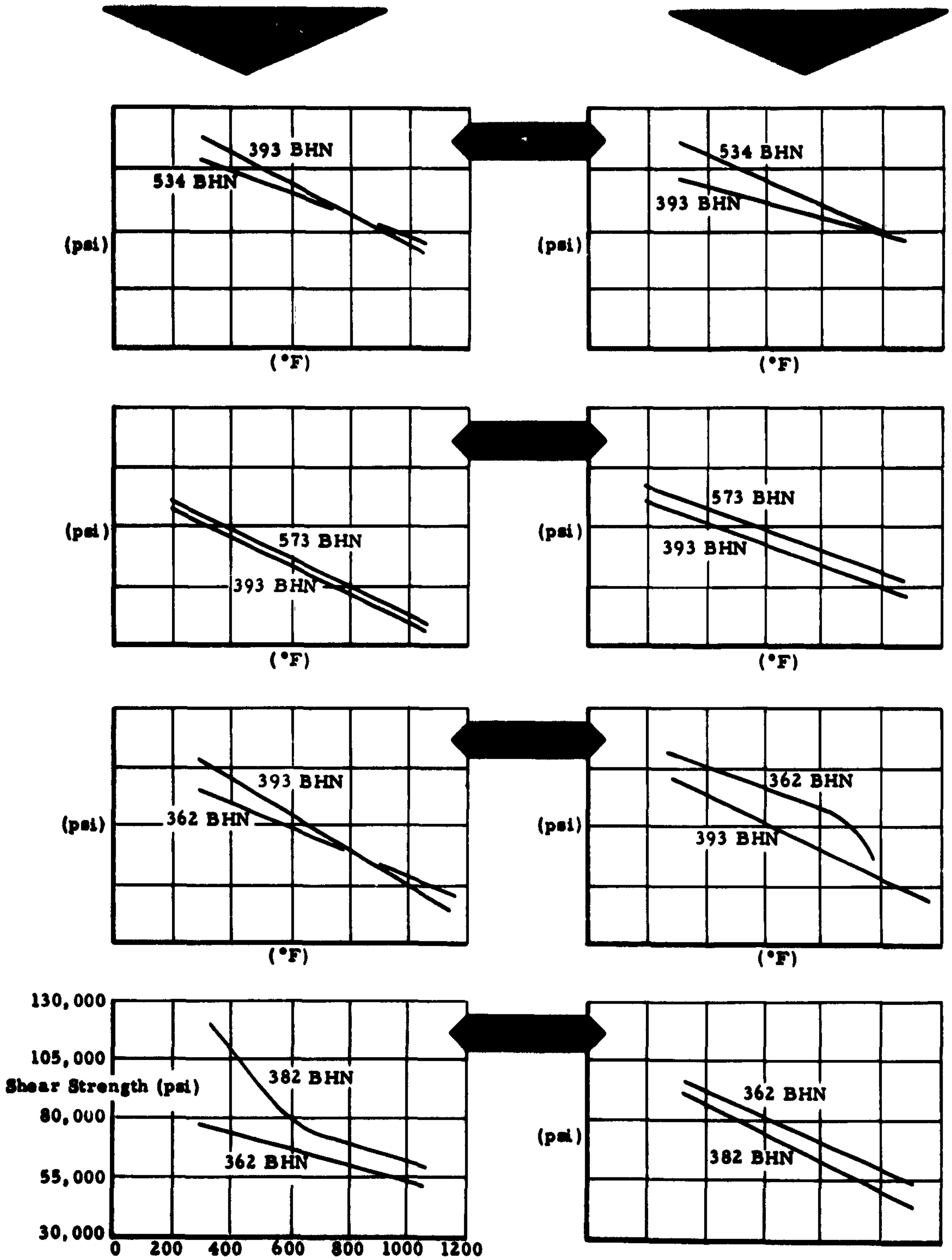


FIGURE 26

EFFECT OF WORKPIECE TEMPERATURE ON THE SHEAR STRENGTH-COMPRESSIVE STRESS RELATIONSHIP AT SHEAR PLANE

Orthogonal Turning
360 - 390 BHN 17-7 PH
250 fpm speed .0048 ipr feed

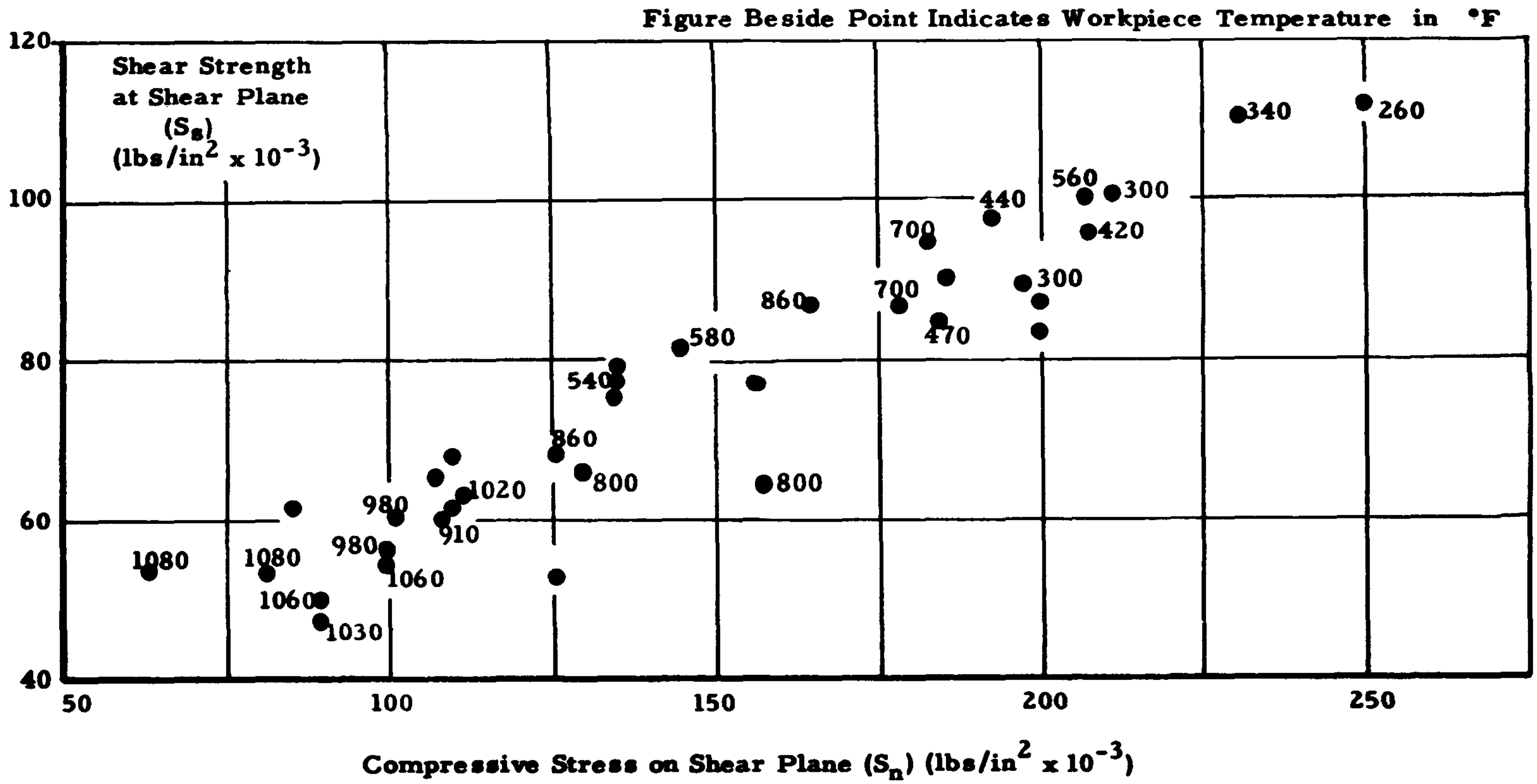


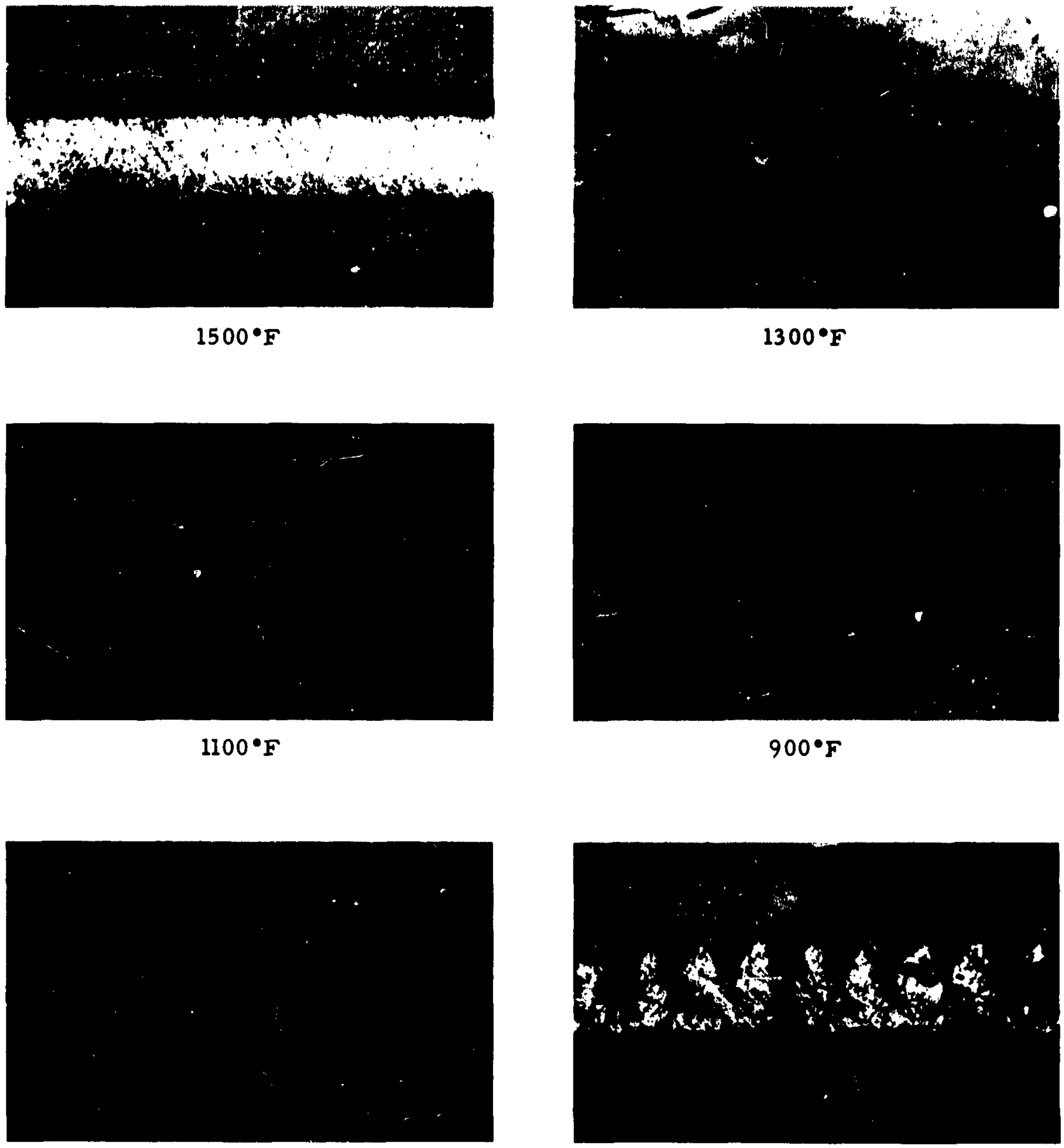
FIGURE 27

EFFECT OF WORKPIECE TEMPERATURE ON CHIP FORMATION

360 BHN AISI 4340

Cutting Speed 124 FPM

Feed 0.004 ipr



1500°F   1300°F

1100°F   900°F

600°F   300°F

FIGURE 28

EFFICIENCY OF METAL REMOVAL AT VARIOUS WORK TEMPERATURES
TURNING OPERATION ON 390 BHN AISI 4340 STEEL

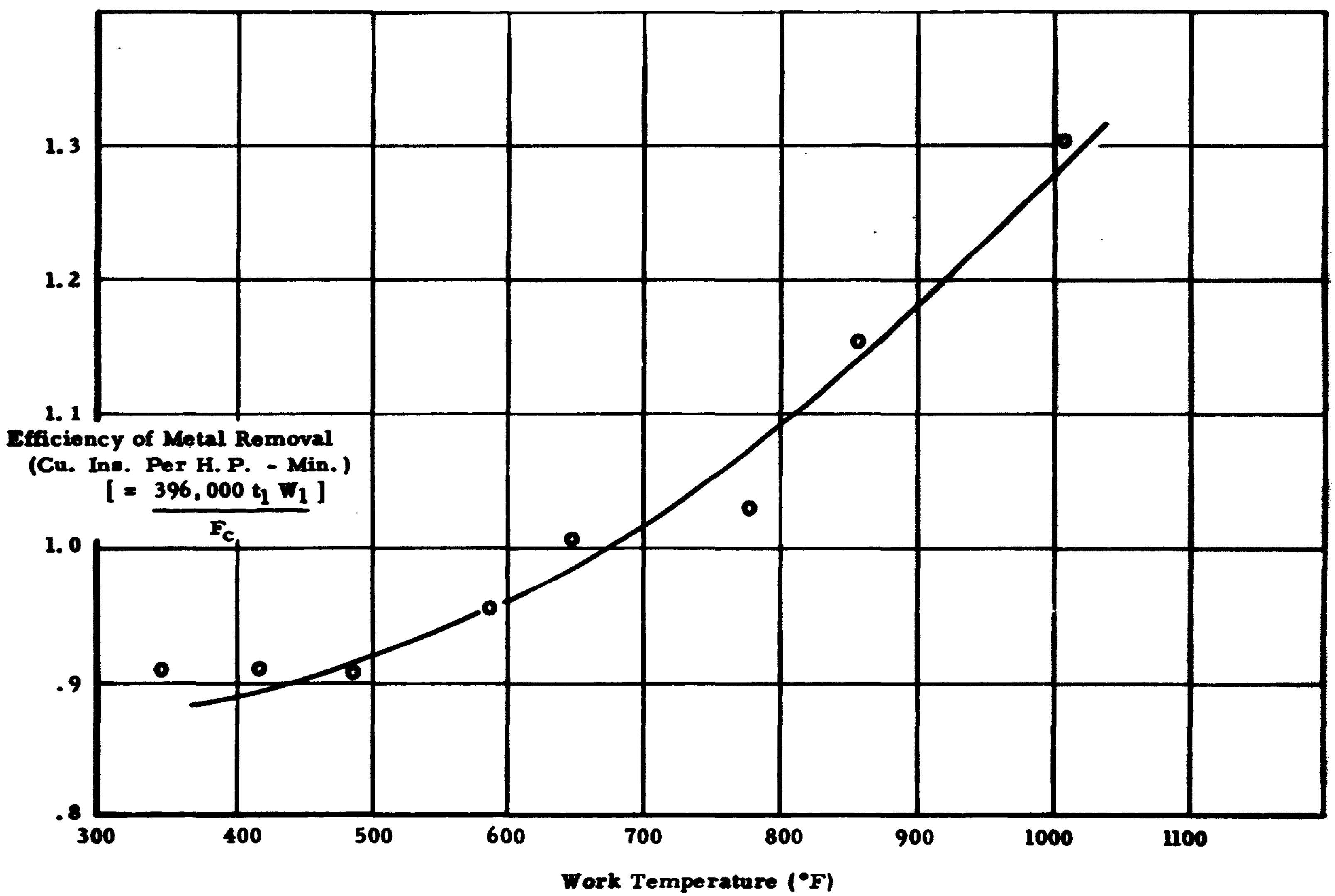


FIGURE 29

EFFECT OF WORKPIECE TEMPERATURE ON THE AMOUNT OF WORK DONE IN:

SHEARING OF METAL (W_s)
OVERCOMING FRICTION (W_f)
CUTTING THE METAL (W_c)

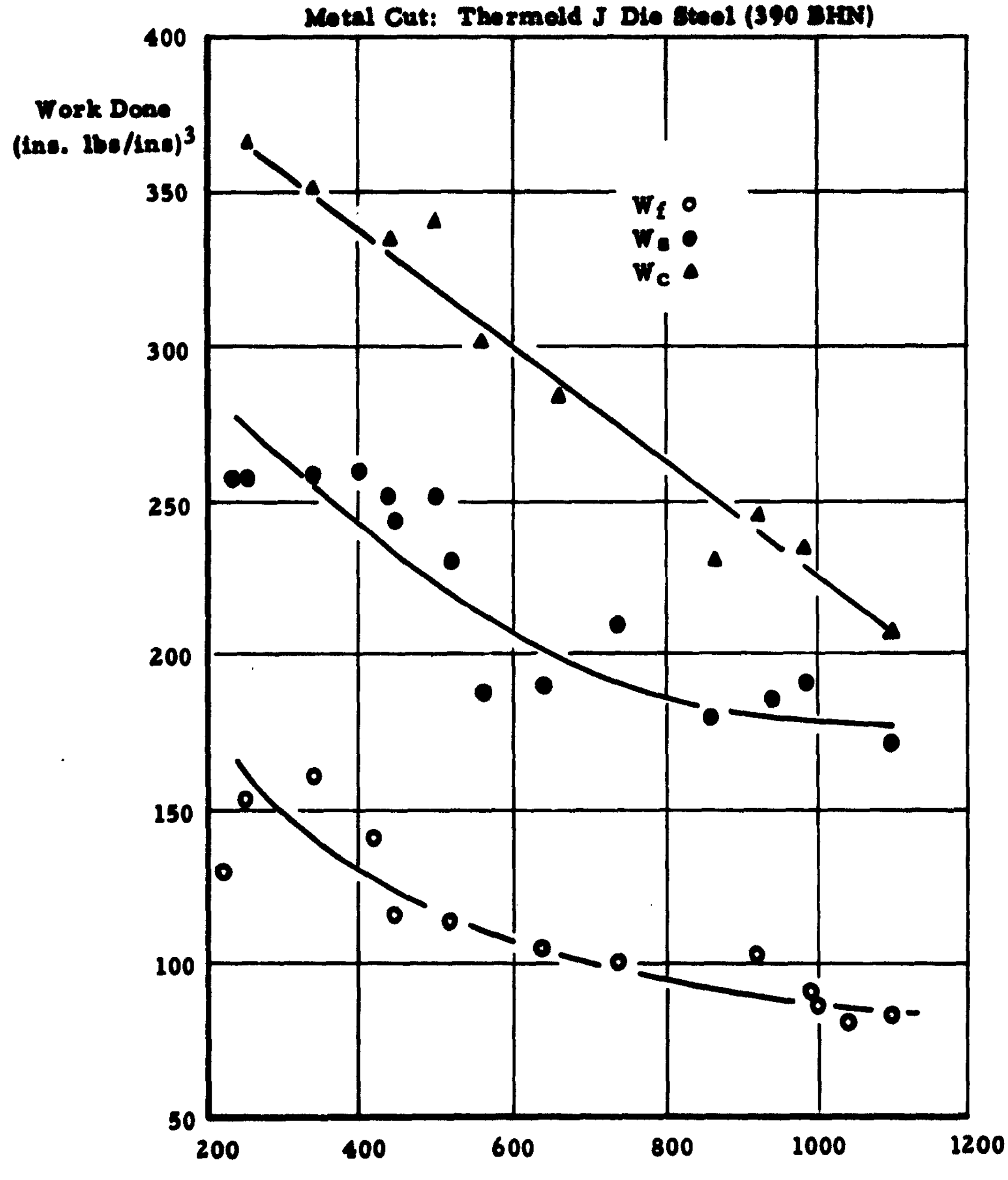


FIGURE 30

TURNING TESTS

Objectives

Obtain cutting speed tool life relationships in turning the various workpiece materials at several elevated temperatures, and develop practical hot turning techniques.

Apparatus

These tests were conducted in the Physical Research Department of The Cincinnati Milling Machine Co., a portion of which, shown in Figure 31, was devoted to research in elevated temperature machining. The machinability tests were conducted on a 21-1/2 Cincinnati Tray-Top lathe, powered by a 10 HP variable speed motor. The tests to determine horsepower requirements in hot machining were conducted on a 15 x 42 Cincinnati Tray-Top Tracer Lathe equipped with a 7-1/2 HP motor as were the economic evaluations described later. Workpieces were brought to desired elevated temperatures by means of a 30 KW, 1.2 megacycles per second Cincinnati Inductron induction heating machine. The "Inductron" was connected by feed lines to the heating apparatus, which consisted of induction or radio-frequency resistance heating equipment. Both induction heating and radio-frequency resistance heating apparatus and techniques are described in detail in the heating section of this report. The type of heating method used is indicated on each figure. To determine the temperature of the workpiece as it enters the cut, a Brown radiomatic radiometer was focused on an area of the workpiece just ahead of the cutting tool during the earlier tests. In later tests a Termodot radiation thermometer was substituted. Throwaway cemented oxide and cemented carbide tools were used in these tests. Tool geometry was: side and back rake -5°, clearance angle 5°, nose radius 1/32" and side cutting edge angle 0 and 15°. The tool life endpoint criterion was taken as 0.015 inch flank wear as measured on a Toolmakers microscope.

Discussion of Results

Figure 32 shows the cutting speed tool life relationship obtained with the workpiece material being cut at room temperature, 300°F, 600°F, and 900°F, when turning 600 BHN, AISI 4340/steel. The other cutting conditions are recorded on the graph. Comparing the results, it can be seen that at 170 feet per minute cutting speed, tool life is increased from less than two minutes at room temperature to 2-1/2 minutes at 300°F, to about 13 minutes at 600°F, and about 35 minutes at 900°F. In other words, there is about a twenty-fold increase in tool life by increasing the workpiece temperature from room temperature to 900°F. Conversely, it is apparent that if a twenty minute tool life were desired, the permissible cutting speed at room temperature under this set-up would be 95 feet per minute. Whereas, at 900°F the speed could be raised to 205 feet per minute.

The cutting speed tool life relationships, of Figure 33, obtained when turning 450 BHN, 17-7 PH at room temperature and at 650°F show that at 200 feet per minute a tool life of four minutes was obtained at room temperature, while a tool life of 28 minutes was obtained at 650°F -- a seven-fold increase in tool life. If a 10 minute tool life was desired, the speed could be increased from 160 feet per minute at room temperature to 240 feet per minute at 650°F -- a 50% increase in permissible production rate.

No hardness loss was measured with the portable Brinell tester after machining at this elevated temperature, but the surface had a light oxide layer that gave it a straw colored appearance.

The results of 400 BHN, 17-4 MO in hot turning were not quite as dramatic, though there were gains to be achieved, as shown in Figure 34. Here about 2-1/2 minutes at room temperature to 7-1/2 minutes at 600°F and to about 11 minutes at 900°F, roughly a five-fold increase in tool life under these conditions. Comparing on the basis of a desired 10 minute tool life, at room temperature the required cutting speed would be 350 feet per minute. At 900°F about 460 feet per minute would be the required cutting speed. This represents a 30% increase in productivity.

The cutting speed tool life relationships shown in Figure 35 were obtained when turning 600 BHN Thermold J workpiece at room temperature, 450°, 600° and 800° with oxide (ceramic) tools. The specific cutting conditions are recorded on the graph. Oxide tools were chosen for this test because they are relatively temperature insensitive and because carbide tools were unable to satisfactorily cut this material at room temperature.

At 500 feet per minute a tool life of 30 seconds was obtained at room temperature, eleven minutes at 450°, 15 minutes at 600°, and 20 minutes at 800°F. Thus, a forty-fold increase in tool life was obtained by elevating the workpiece temperature from 76° to 800°F. At temperatures below about 650°F no surface discoloration or hardness loss was found. However, at higher temperatures the surface was slightly oxidized and the hardness dropped from 600 to 555 BHN when machining at 800°F when measured with the portable Brinell tester.

Because of the absence of workpiece metallurgical damage at 650°F and therefore its applicability to production operations, this temperature was selected for further studies of the effect of feed rate on tool life. This temperature was also obtainable with a 30 KW Inductron and easy to control at all feed rates that were to be tried. Tests were run at .002, .004, .006, .008, .010, and .012 ipr. The results of these tests are presented in Figure 36 which shows a plot of flank wear versus volume of metal removed for each feedrate. The graph shows that more metal can be removed per tool life at .004 ipr than any other feed. When feeds of .010 and .012 ipr were used, failures were by instantaneous shattering. It is possible, of course, that the 50% increase in metal removal rate can economically offset the 23% decrease in metal removed per tool when .006 ipr is used. The sharp decrease in tool life when cutting at .008 ipr could probably not be justified economically.

Surface finish was excellent on all turning tests, although some oxidation to the extent of discoloration was encountered at some of the elevated temperatures used.

Long straight chips were obtained during cutting and these did not respond to normal chipbreaking techniques. No attempt was made to solve this problem other than to try unsuccessfully various chipbreaker designs.

The tool life tests on Thermold J showed the greatest response to hot machining -- forty-fold. This was due in part to the fact that the high strength and hardness of this material made it difficult to machine and consequently even a small improvement in tool life was a large percentage increase. It is also true that a specimen of material at high hardness loses strength more rapidly than one at low hardness. The strength of specimens converge with increasing temperature regardless of their initial strength level. In addition, this test is the only one where oxide tools were used. The ceramic tools were less heat sensitive having a shallower slope of the temperature versus strength curve than carbide tools. This means that when the workpiece temperature and consequently the tool chip interface temperature is increased, a ceramic tool loses less strength than does a carbide tool for comparable loss in workpiece strength.

The high work material strength also caused the optimum feed rate to be relatively low because of the shattering of the cutting tool at higher feed rates. While no tests were run to determine the optimum feed for machining at room temperature, it might be expected that both the optimum feed, and the feed where shattering occurred would be lower.

The machining conditions used for the economic comparisons on the truck pivot were chosen to fully utilize the limited horsepower available. The 7-1/2 hp tracer lathe available for experimental use was smaller than would be desired. However, the lack of horsepower is also a problem in industry. It is felt that often metal removal rates are not limited by tool life but are dependent on the horsepower available. This is not always obvious since the high cutting speeds and feeds are maintained, but the depth of cut is often reduced to accommodate the lack of horsepower even though workpiece deflection is not a problem.

It was decided, therefore, to determine the unit horsepower (hp/cu in. /min.) for the "as received" material at room temperature and the heat treated material at the selected optimum elevated temperature, and from these data choose cutting conditions that would utilize all of the available power.

Tool life-cutting speed curves determined at different temperatures show that the largest rate of improvement in tool life is obtained at the lower temperatures. In Figure 35, it can be seen that the tool life can be increased twenty-two-fold by increasing the temperature to 450°F, but can only be increased 82% more by increasing the temperature from 450°F to 800°F. In addition, a higher temperature increases the chance of metallurgical damage.

The tempering temperature to obtain the strength and hardness required for this part is 775°F. It was, therefore, decided to conduct all tests and evaluations at 700°F to insure that no metallurgical damage occurred.

A recording wattmeter was connected across the power input to the motor, and after determining the tare power, cuts were made to determine the gross power. The net power required for cutting was determined by subtracting the tare from the gross power, this was then divided by the metal removal rate to obtain the unit horsepower, i.e.,

$$\text{unit horsepower} = \frac{\text{gross power (hp) - tare power (hp)}}{\text{metal removal rate (cu in./min)}}$$

The unit horsepower required when machining the "as received" 4340 at .010 ipr feed was 0.60 and for the 47 Rc 4340 at 700°F and .010 ipr feed was 0.67. By using a 10% safety factor to allow for dull tools and a 70% mechanical efficiency for the lathe drive, it was determined that a metal removal rate of 6.75 cu in./min could be obtained with the 7-1/2 hp motor in either as received stock at room temperature, or heat treated stock at 700°F.

The cutting conditions chosen to yield a satisfactory tool life were to be 450 fpm cutting speed, .010 feed, and .125 depth of cut for conventional machining. A cutting speed of 500 fpm with a .0091 feed and .125 depth was chosen for machining at 700°F because better chip control resulted. In either case, 6.75 cubic inches of stock were removed per minute.

HOT MACHINING LABORATORY
Lathe with R. F. Resistance Heating, 1.2 Mc Induction Heating
Machine and Vertical Milling Machine with R. F. Induction Heating

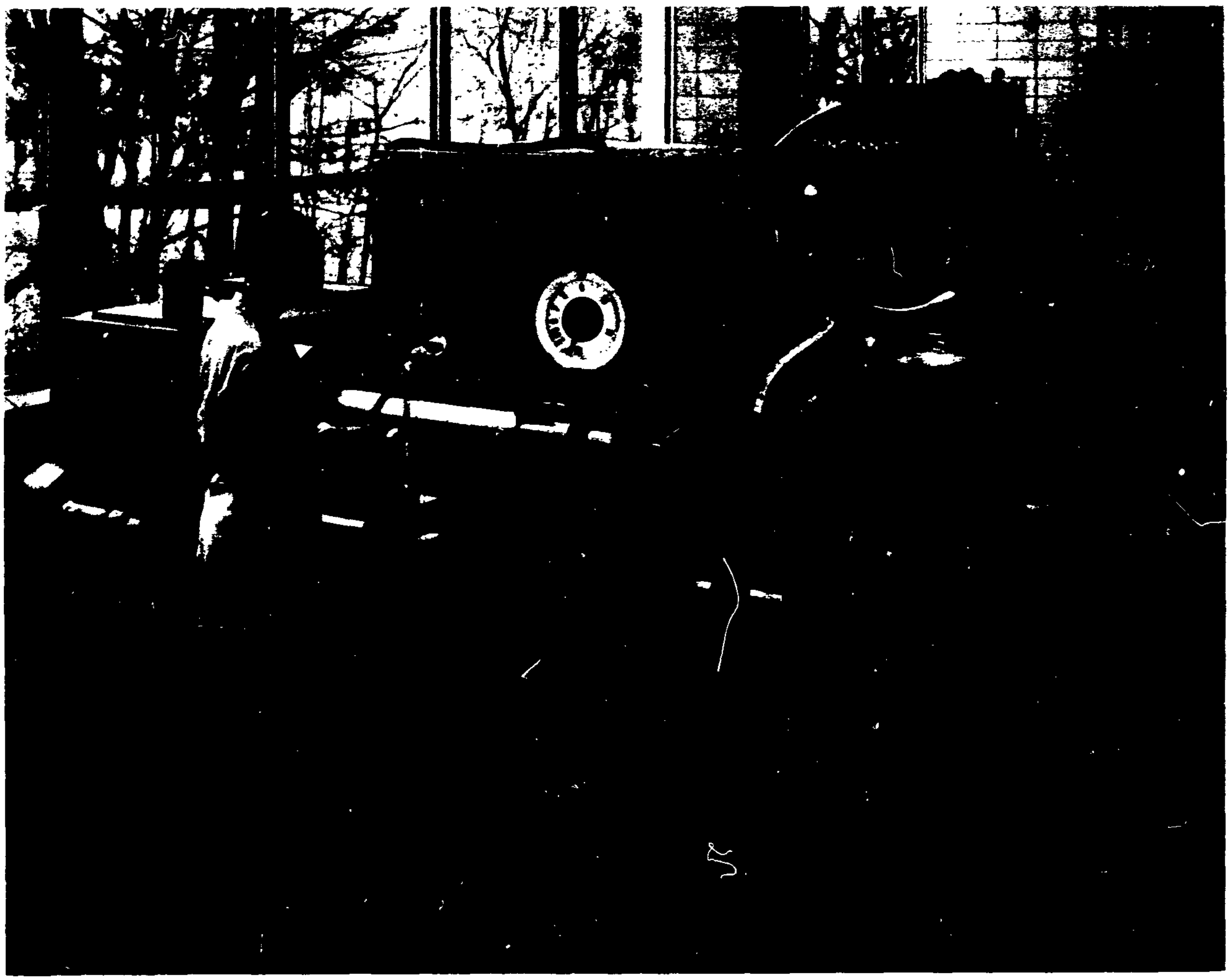


FIGURE 31

EFFECT OF TEMPERATURE ON TOOL LIFE-
CUTTING SPEED RELATIONSHIP

TURNING 4340 STEEL 600 BHN (59 Rc.)

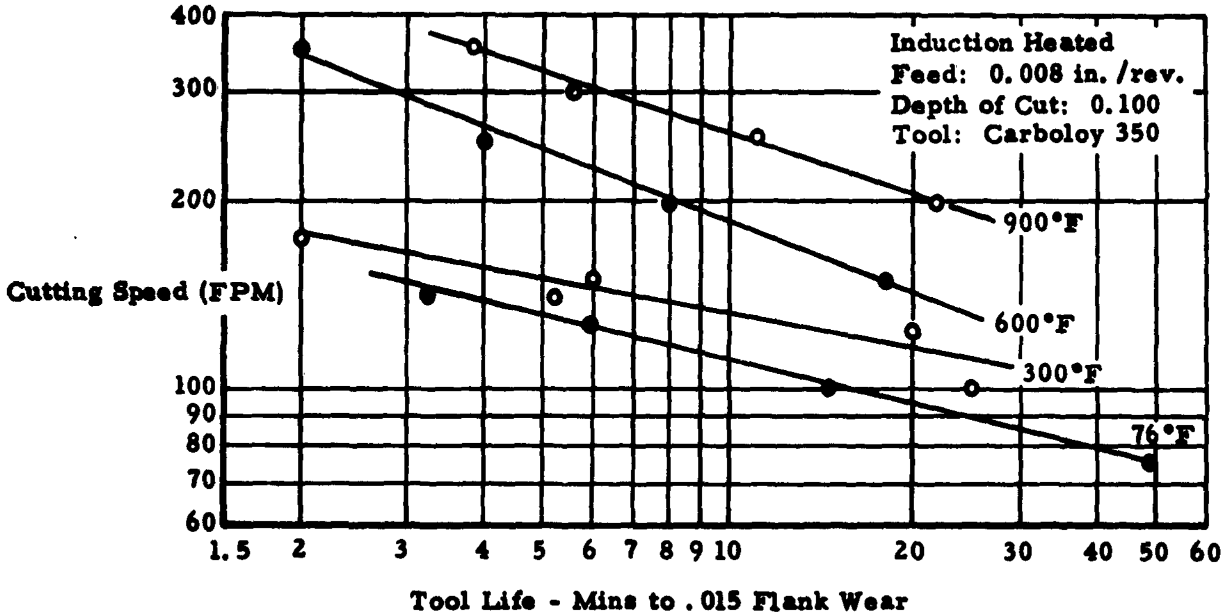


FIGURE 32

EFFECT OF TEMPERATURE ON TOOL LIFE
CUTTING SPEED RELATIONSHIP
TURNING 17-7 PH 450 BHN

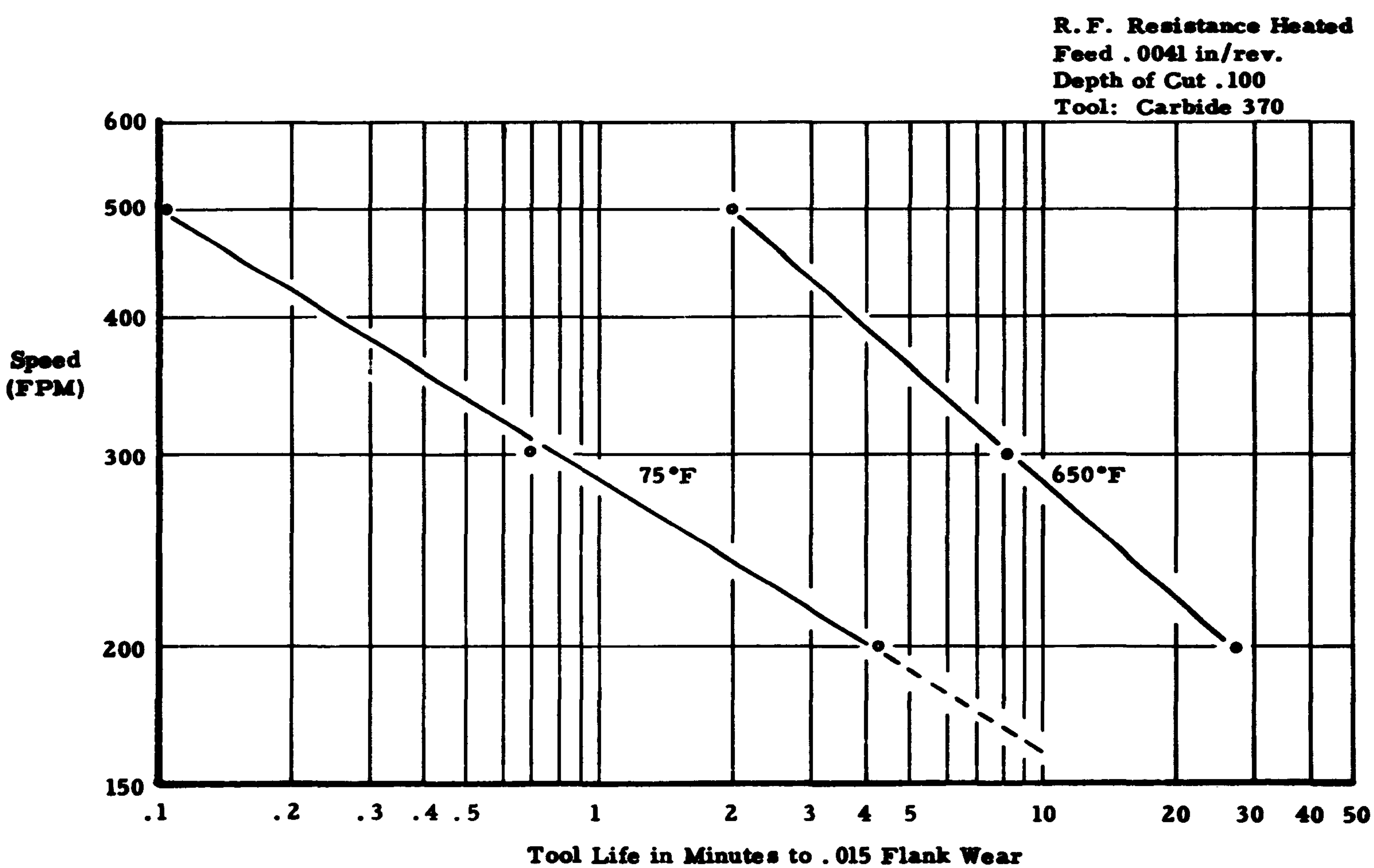


FIGURE 33

EFFECT OF TEMPERATURE ON TOOL LIFE-CUTTING SPEED RELATIONSHIP

TURNING 17-4 Mo STEEL 400 BHN

Induction Heated
Feed: 0.008 in./rev.
Depth of Cut: 0.100 in.
Tool: Carboloy 350

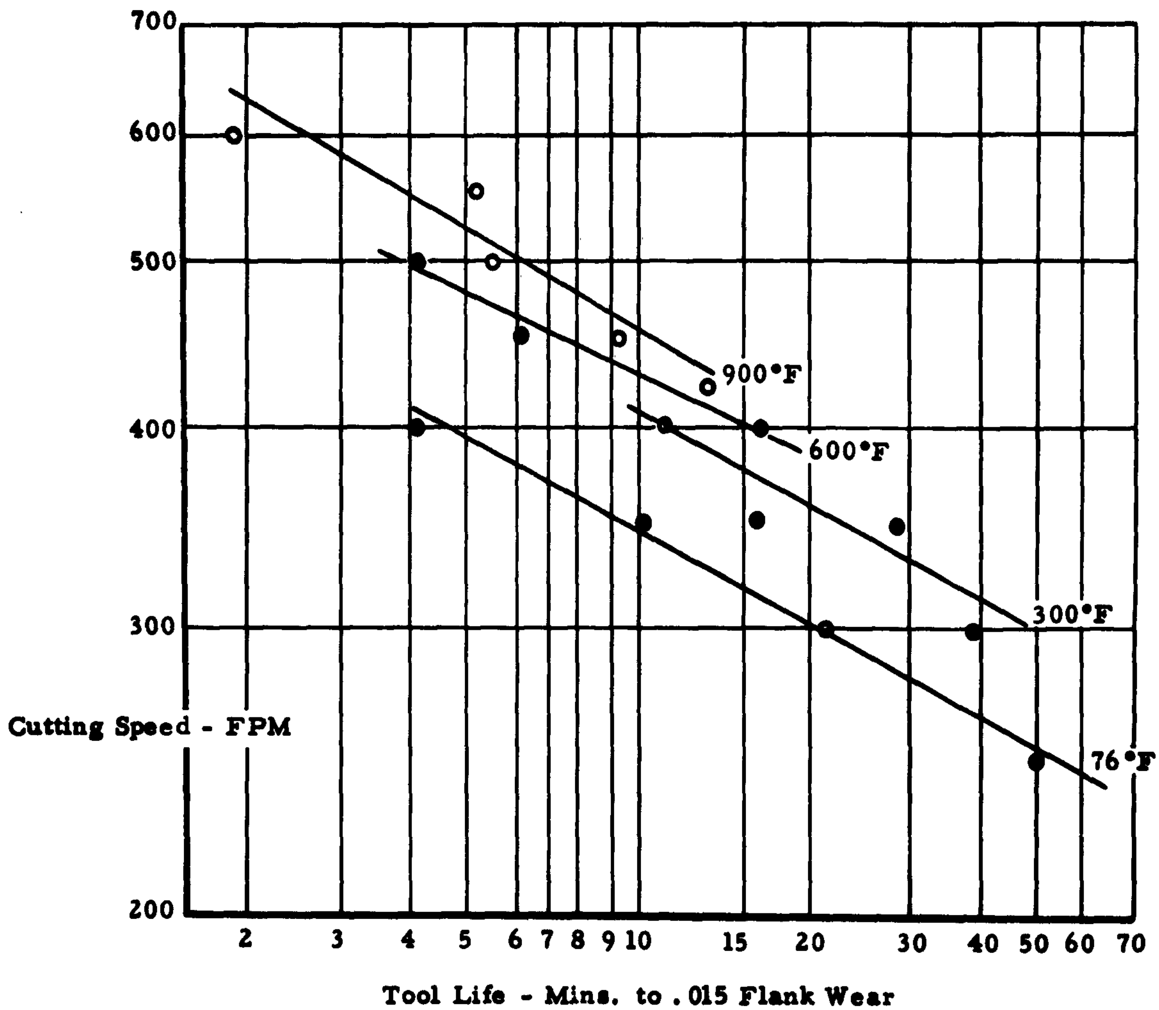


FIGURE 34

EFFECT OF TEMPERATURE ON TOOL LIFE -- CUTTING SPEED RELATIONSHIP

TURNING THERMOLD J 600 BHN (60 Rc)

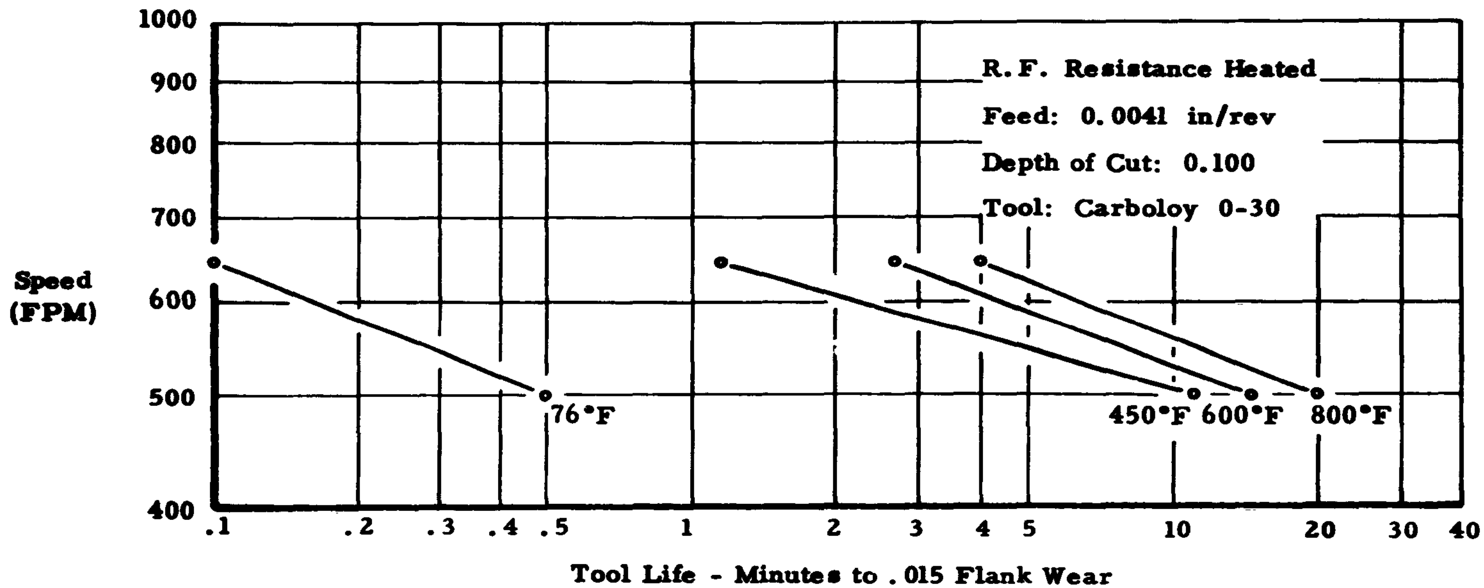


FIGURE 35

FLANK WEAR VS. FEED WHEN TURNING THERMOLD J AT 650°F

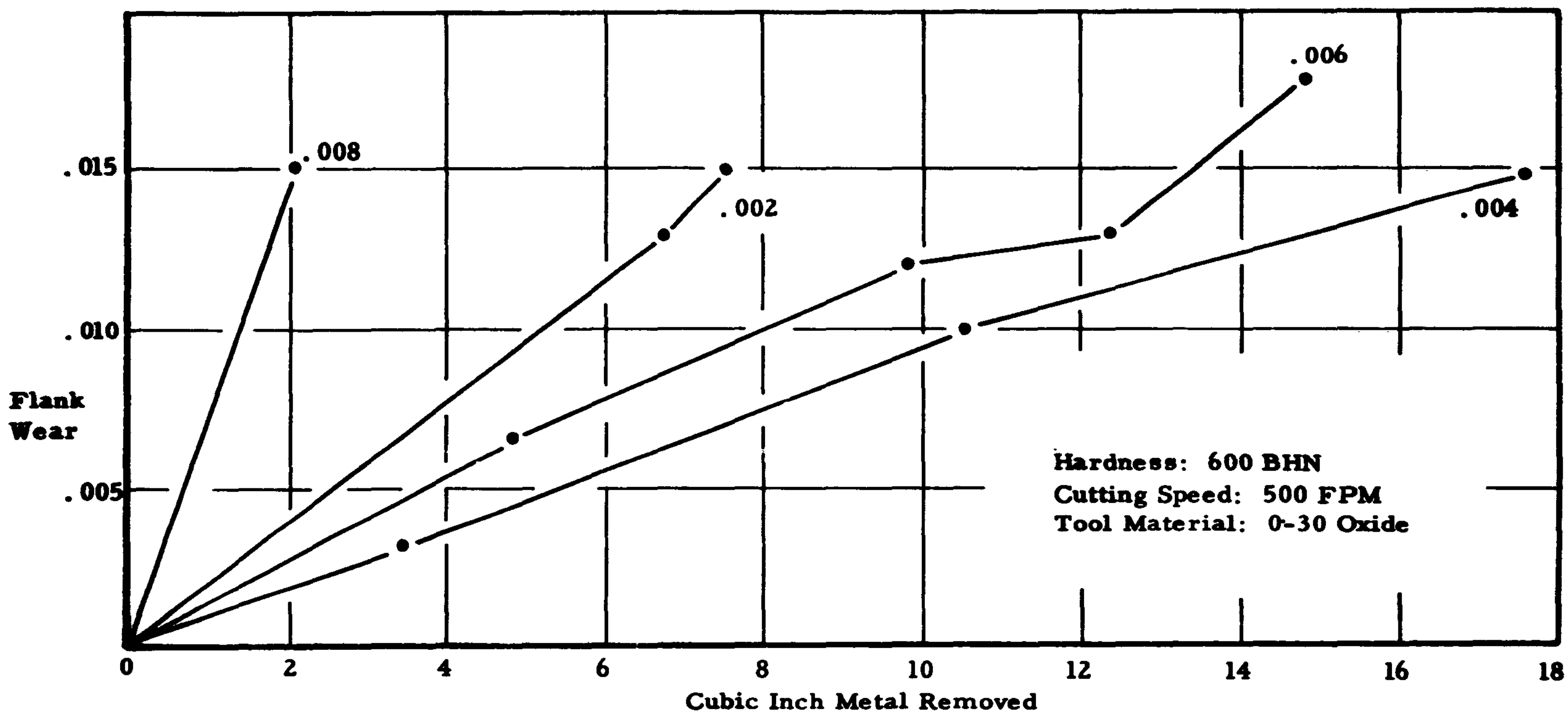


FIGURE 36

FACE MILLING TESTS

Objective

Evaluate the practical significance of hot milling by running tool life tests over a range of workpiece temperatures of work materials and use the results in the development of a workable technique for milling at elevated temperatures. Evaluate solid and vaporous lubricants at room temperature and at various elevated temperatures to determine their effect on tool forces, temperature and life.

Apparatus

Tests were run on a Cincinnati No. 3 Vertical Dual Power Milling Machine. Power to heat the magnetic workpiece materials were supplied by a "Cincinnati "Inductron", a 1.2 megacycle, 30 KW Induction heating unit. In the case of non-magnetic materials the heating power was supplied by a 400 amp - 40 volt D.C. welding machine. Some of the preliminary tests on the refractory materials utilized furnace heating. The type of heating method used is mentioned in the subsection describing the particular tests and the heating apparatuses are described in the heating section of this report. The tool-work thermocouple used in some of the milling tests was arranged in much the same way as that described under orthogonal turning tests. However, as shown in the schematic diagram in Figure 37, two compensating circuits were used to nullify the parasitic EMF generated at the junction of the leads at the carbide tool and the hot workpiece. To determine the high forces encountered in machining high strength materials, a high stiffness 3 axis milling dynamometer was built. The body of the dynamometer without guards is shown in Figure 38. It was machined from an AISI 8650 steel forging. The top plate measures 6-3/4 by 9-1/4 inches and is separated from the bottom by a bandsaw cut. Both portions are joined together by four half octagonal rings, one at each corner, which were machined from the solid forging. As can be seen from the photograph, adjacent rings are at right angles to each other, diagonally opposite rings being parallel. The SR4 type strain gages are mounted at the points of stress concentration, three on the outside and one on the inside of each half ring, such that the force readings are made in the vertical, longitudinal and transverse directions. The stiffness of the dynamometer was calculated to be in the order of 87,000 lbs per inch in the horizontal direction. The natural frequency which varies with the suspended weight is in the order of 300 cycles per second. In all face milling tests throwaway carbide tips were used. Of particular interest is a face mill which consisted of modified throwaway insert cutting tool holders clamped to the cutter body. The cutter body was constructed and balanced, so that either single tooth or four teeth could be used. The four tooth cutter was used at low cutting speeds to allow a higher table feedrate for more localized heating. The tool life end point criteria was taken as 0.030" flank wear. The cutter was considered to have failed when the tooth reached this wear, or in the case of the four tooth cutter when two of the teeth exceeded it. This eliminated, in the case of the four tooth cutter, the undue influence of a high tooth.

Unless otherwise stated, in all milling tests, Carboloy 370 single-tooth carbide cutters were used with axial and radial rakes of -7°, 15° corner angle, and 1/16" nose radius.

The dimensions of the workpieces used in the face milling tests were 1" wide x 12" long x 5" initial depth.

Discussion of Results

Figure 39 shows the results obtained when face milling 380 BHN 17-4 MO stainless steel on the induction heated set-up using a single-tooth, 370 carbide cutter. It can be seen that, in the cutting speed range used, tool life is less than one-half minute with workpiece at room temperature, is in the region of 5 minutes to 20 minutes at 400°F, and is 12 minutes to

50 minutes at 1000°F workpiece temperature. Flank wear of the tool of 0.030" was taken as the tool life criterion. For comparison, the cutting speed-tool life relationship when conventionally milling 150 BHN C 1018 steel under the same cutting conditions is shown on the graph. So it is seen that a one-hundred-fold increase in tool life was obtained by elevating the temperature of this 380 BHN material to 1000°F and that this tool life obtained by hot machining was approximately equivalent to that obtained when conventionally machining a soft C 1018 steel.

Similar results are shown in Figure 40 for 390 BHN Thermold J die steel where tool life is much improved by elevating the workpiece temperature.

In face milling tests, the angle of engagement between tool and workpiece as the cutter entered the cut during each revolution was found to have influence on the length of tool life. This angle is dependent upon the distance between the engagement face of the workpiece and the axis of the cutter, and the diameter of the cutter. These, together with the geometry of the cutting tool, determine the type of initial contact which occurs between tool and work each time the tool enters the workpiece.

Figure 41 shows tool life-engagement angle relationships for test cuts on 390 BHN AISI 4340 steel at 1020°F, 390 BHN Thermold J die steel at 1020°F, and 360 BHN 17-7 PH stainless steel at 890°F. The optimum engagement angle appears to be around -10° for maximum tool life. Drawn into Figure 41 is an explanation of the type of initial contact occurring at each engagement angle for the cutting configuration used in these tests and a sketch of the cutting tool showing the points or lines of contact marked S, T, U, V. Normally, U contact gives best results with carbide tooling since the impact force during the intermittent cut is located back from the mechanically weak cutting edge. However, UT to T contact appears best in this application. Figure 42 shows a sketch of the paths of cutting of the 6" diameter cutter as it passes through the 1" wide workpiece for the different engagement angles tried. Also shown is the type of initial contact for each condition. It seems logical that tool life should fall off towards +30° or -30° engagement angles since the duration of the tool in the hot workpiece is longer. However, later on in further studies, as indicated in the refractory section, these were much higher.

Tool Materials: Tests were conducted to evaluate the performance of various types of tool materials, such as carbide, cermets and oxide (ceramic) tools. Figure 43 shows the tool wear curves obtained for these four tool materials when face milling 500 BHN Thermold J die steel at 950°F. Various cemented oxides or ceramic tools were tried with little success, presumably due to their low transverse rupture strength, which does not allow ceramics to withstand the repeated severe impacts of these milling cuts. Two cermets which are essentially titanium carbide with a nickel binder showed some improvement over ceramics. However, the lowest wear rates were obtained using cemented carbide tools, which apparently have the best known combination of physical properties for this type of operation. The best of several grades tried is shown on the graph, namely grade 370.

Rake Angles: To determine the most effective radial rake in hot milling, tools with a -7° axial rake and various radial rakes were tried when face milling. The results of these tests on 500 BHN Thermold J at 950°F are depicted in Figure 44. The best performance was obtained with a radial rake angle around 0 to -7°. Positive rakes gave a mechanically weak cutting edge and an inferior tool wear rate, presumably due to the increased cutting forces which resulted.

Tool Life vs. Interface Temperature: In further analysis, the results obtained during the previously run tests on 380 BHN 17-4 MO steel are illustrated graphically in Figure 45. What is shown is a plot of tool life against average tool chip interface temperature, as measured during face milling cuts with 4 different cutting speeds at various workpiece temperatures from 240°F to 1050°F. Enclosing the points in an envelope, it can be seen that there is an optimum range of temperatures at the chip tool interface where the best tool life is obtained. This range is 2100°F to 2450°F for the particular cutting conditions used here. Below 2100°F tool temperature, the situation exists of low workpiece temperature with consequent high strength and hardness of the work material, and high tool forces. All of these factors accentuate abrasive and fracture wear of the tool, giving brief tool life. Above about 2450°F chip-tool interface temperature, which situation occurs at higher cutting speeds and workpiece temperatures, welding between the chip and tool predominates and the tool wear process becomes acute with rapid breakdown of the cutting edge.

Nickel and Cobalt Base High Temperature Alloys: Evaluations to determine the temperature at which maximum tool life could be obtained when face milling and then to determine the cutting speed-tool life relationship at room temperature and the optimum temperature were conducted on Rene' 41, Inconel X, and Haynes Alloy No. 25. In addition, the effect on tool life of placing asbestos at the entry to the cut was studied.

A plot of tool life vs. workpiece temperature under constant cutting conditions for Rene' 41 is given in Figure 46. This curve shows that tool life decreases slightly when the temperature is increased, but then increases rapidly to a maximum value at approximately 1960°F.

The effects of cutting speed on tool life at room temperature and an optimum elevated temperature are shown in Figure 47 for face milling Rene' 41.

When milling with the workpiece at room temperature and at a cutting speed of 110 fpm a tool life of 4.4 minutes was obtained, while at the optimum temperature (1935-1985°F), a 7.7 minute tool life may be obtained. If a ten minute tool life is adequate, production rate can be increased one-third by increasing the cutting speed from 73 fpm at room temperature to 97 fpm at the optimum temperature.

In addition, if asbestos sheets are placed at the entry, so that the tool cuts them before it contacts the Rene' 41, the tool life at 110 fpm is increased to 15.5, minutes and the cutting speed for a ten minute tool life to 200 fpm. An explanation of this 260% increase in metal removal over room temperature is given in the section "Asbestos as a Metal Cutting Lubricant".

Figure 48 illustrates the workpiece temperature-tool life relationship found when face milling Haynes Alloy No. 25. Tool life increases with increasing temperature to a peak around 800°F; it then falls back before rising to a lower peak around 1500°F. This unusual relationship is quite similar to the ductility vs. temperature curve for sheet stock.

The tool life-cutting speed curves for Haynes 25 (Figure 49) show that at 150 fpm the tool life increases from 3.9 minutes at room temperature to 11.2 minutes at 800°F. Similarly, for a 10 minute tool life, the cutting speed can be increased from 94 fpm at room temperature to 160 fpm at the optimum temperature.

The use of asbestos at entry further increases the tool life to 38 minutes and the permissible cutting speed to 370 fpm which is a four-fold increase in metal removal rate over that possible at room temperature.

Depicted in Figure 50, is the workpiece temperature-tool life relationship for Inconel X. It shows a steady increase in tool life with increasing temperature until approximately 1450°F is reached and then a sharp drop.

A tool life increase from 1.8 minutes to 17.5 minutes is shown in Figure 51 when the work temperature is increased from room temperature to 1450° when face milling at 150 fpm. A production rate increase of 230% -

57 fpm to 190 fpm - with a 10 minute tool life can be obtained. The use of asbestos further increases the tool life to 35 minutes or the cutting speed to 270 fpm.

When cutting these materials it was found that the chip tends to weld to the carbide insert and to be carried around with the cutter. To prevent the chip from being crushed off the cutter when it re-enters the work, with consequent damage to the cutting edge, a "chip picker" consisting of a strip of spring copper was devised. This knocked the chip from the cutter in a brushing action while it was hot and before it was crushed against the work.

Removing the chips from the cutter, before they are carried around and crushed against the workpiece, is of greater importance at elevated temperatures. In one case the use of the chip picker increased the tool life from two minutes to three minutes at room temperature, but increased the life from one minute to nineteen minutes at elevated temperature under otherwise identical cutting conditions. This, of course, results from the greater welding between tool and chip at the higher workpiece, and thus cutting temperatures.

Figures 46 and 50 plot the workpiece temperature against the corresponding tool life for Rene' 41 and Inconel X respectively. It can be seen that the curves are steep and that only a small change in temperature can cause a large change in tool life. Also, a small addition of heat above the optimum temperature causes a rapid drop in tool life.

These phenomena result, it is felt, from two facts:

(1) The material does not exhibit much loss in strength until a high temperature is reached (1200-1400°F as shown in Figure 13).

(2) The nature of the wear is welding and plucking out of the tool material which increases rapidly with increasing tool temperature.

When the workpiece temperature is elevated to some temperature near but below that which causes a significant decrease in strength, it exhibits the disadvantage of hot machining, i.e., the increase in tool-chip interface temperature without the advantages of lower cutting forces. This results in a higher rate of tool wear and shorter tool life. This phenomenon probably also occurs in steel but at such a low temperature that the corresponding increase in interface temperature seldom causes a significant change in tool life because the tool life-interface temperature relationship is hyperbolic and a small change at low temperatures has little effect compared to the same change at high temperatures (for an exception see the section "End Milling" in this Report).

As the workpiece is heated to still higher temperatures, the temperature is exceeded where a significant reduction in strength has occurred. This causes a sharp increase in tool life. However, when the temperature is raised only a little more, with a consequent increase in tool-chip interface temperature, welding becomes severe and tool life plummets.

The wear on the cutting tools is not always of the normal type usually experienced in machining steel. Figure 52 illustrates some examples of this: Figure 52(a) shows a fairly normal abrasive wear of the edge in places; Figure 52(b) shows a chipping and welding wear failure; Figure 52(c) is the start of the most common tool failure experienced -- abrasive wear over the depth of cut, and chipping at the surface of the metal; Figure 52(d) shows this wear at failure of the tool.

The chipping in 52(c) and (d) appears to be of a thermal nature. It occurs at the boundary of the hot interface area and the relatively cool part of the tool where stresses are set up due to uneven thermal expansion. Similar chipping has also been found on occasion when turning 600 BHN Thermold J with oxide tools.

Further tool life tests were conducted at room and elevated temperature on a 4" wide solution treated Rene' 41 workpiece. The results shown in Figure 53 indicated that even at 1980°F, the experimentally determined optimum elevated temperature, the tool life was inferior to the room temperature tool life. It was felt that the workpiece width might have a large effect on tool life since the tool would be buried in the hot work for a longer time. Tool life tests were run on a 2 inch wide workpiece. The results in Figure 54 again show that room temperature tool life is greater than that at elevated temperature though by a lesser amount.

Machining a 2" wide Rene' 41 workpiece in the aged condition improved the elevated temperature tool life over the tool life when the material is in the solution treated condition. Unfortunately, as Figure 55 shows, the room temperature tool life is also increased so that no benefits result.

Changing the cutter geometry from 0° radial rake, +7° axial rake to -5° radial rake, -5° axial rake again, as shown in Figure 56, increased both room and elevated temperature tool lives.

To fully determine the effect of workpiece width on tool life, tests were run at both room and elevated temperature on 1, 2, and 4 inch wide aged Rene' 41 workpieces with grade K6 carbide and negative rake angles. The results in Figure 57 show that with a 4 inch width of cut hot machining is 60% inferior to room temperature, with a 2 inch width the tool lives are equal and with a 1 inch wide workpiece hot machining gives a 66% increase in tool life over that obtained at room temperature.

The above findings indicate that the tool life at elevated temperature is dependent on the length of time it is subjected to these high temperatures. In the case of the four inch wide workpiece the cutter is buried in the very hot (1980°F) work material for a much longer time than with the one inch work. The same phenomenon can be seen by comparing results of face milling and turning tests on various steels at elevated temperatures. In all cases the tool life improvement due to hot machining is less for turning, where the tool is buried for a long period of time, than it is for milling where the tool is heated for only a short period. However, in the cases of the various steels, the tool life improvements are so large for milling that a small reduction in improvement is not important. On the other hand, with Rene' 41 the tool life improvement was only three-fold when milling narrow workpieces; consequently, even a small loss in tool life would eliminate the benefits.

The problem of the buried tool was also found during the interim between Phases II and III when an attempt was made to determine the optimum temperature for turning a Waspaloy forging for a customer. The octagonal forging was insulated from the lathe and an arc drawn from the torch to the workpiece as shown in Figure 58. A copper brush riding on the tailstock center provided the current return path.

Tool life tests at various temperatures gave these results:

Room temperature	1.8 min
530°F	.75
820	.5
1020	.8
1465	.5
1600	.25

Again, indicating that these high temperature alloys lose little strength until the temperature is too high for the tool buried for an extended period in the workpiece.

Heating is more difficult when hot machining these alloys than for ordinary alloy steel since the metal is non-magnetic and requires, except in the case of Haynes Alloy No. 25, a higher temperature before tool life improvements are obtained. The low permeability of the material precludes the use of induction heating or resistance heating with radio-frequency since relatively good magnetic properties of the material are essential for these heating methods, particularly when temperatures in excess of 1000°F are required.

When arc heating is used, as in the above tests, the arc must be separated from the cutter by at least 3/4 inch to prevent the heat of the arc from damaging the cutter. This means that the material cools for a time equal to 3/4 inch divided by the table feed rate in inches per minute. Cooling time must be kept to a minimum to maintain a minimum temperature drop between the arc and cutter. When the feed rate is high enough, the material under the arc is heated to a temperature only a little higher than that required for the cut, less time is allowed for the heat to penetrate beneath the depth of cut, resulting is less damage to the workpiece and better thermal efficiency. To increase the feed rate and consequently reduce the cooling time, a four tooth cutter was used in these tests in place of the single tooth cutter generally used in the research work. In spite of this number of teeth, the feed could not be maintained at a high enough rate to determine tool life at cutting speeds lower than 107 fpm. However, it is evident that when production type multi-tooth cutters are used lower speeds could be used with sufficient feed rates (fpm) and higher tool lives could be expected.

It should be noted that the use of asbestos at the entry to the cut doubled or tripled the tool life obtained. Studies to determine the cause of this phenomenon are described in the section on "Asbestos as a Metal-cutting Lubricant".

Evaluation of Metal Cutting Lubricants in Face Milling

Introduction: Cutting fluids have long been used effectively in metal working operations in order to improve both tool life and surface finish. Merchant[42] has defined the two basic functions of a cutting fluid as being:

(1) "To remove heat from the cutting tool, workpiece and chips (i.e., cool)."

(2) "To reduce the friction between the flowing chip and the cutting tool, thus reducing the heat generated in cutting and in addition providing other benefits".

The direct way of controlling heat in the cutting operation is not just to remove that heat which is formed but rather to reduce the amount of heat generated due to both plastic deformation of the metal and the friction between the tool and chip. An effective cutting fluid by reducing the friction between the chip and tool can significantly reduce the amount of heat formed in the metal cutting operation.

The reduction of friction at the tool-chip interface serves a two-fold purpose; first, to reduce the amount of energy expended in plastically deforming the metal, and thus the amount of heat generated; second, to reduce the amount of frictional heat generated at the tool-chip interface. If tool-chip interface friction is high, the resultant shear angle is low and the length of the path of shear is great, as may be seen in Figure 59. However, if the friction at the tool-chip interface is lowered, the shear angle is increased and the resultant path of shear is shorter, thus reducing the area under shear and the energy required to shear the metal on this plane. Since more than two-thirds of the heat formed in the metal cutting operation is due to energy expended in shearing the metal, it is not difficult to see that a reduction in the coefficient of friction at the tool-chip interface can materially reduce the amount of heat generated in the metal cutting process. This, in turn, brings the chip to the tool-chip interface at a lower temperature. In addition, when the shear angle is high, the chip is thinner and the force to shear is less, the normal force of the chip against the tool face is also less. This lesser force together with the reduced coefficient of friction results in the development of less frictional heat at the critical tool-chip interface. This, in turn, results in a lower tool-chip interface temperature.

While it does not seem practical to take advantage of the direct cooling capabilities of the cutting fluid in elevated temperature machining, since direct removal of heat from the workpiece is not consistent with the objectives, it should be possible to reduce the friction at the tool-chip interface by interposition of an effective metal cutting lubricant between the chip and tool.

Earlier research conducted in this laboratory, not under the auspices of this research contract, has indicated that the introduction of certain solid lubricants to the milling operation can, under certain conditions, significantly affect metal cutting performance. This research had indicated that when milling steel of medium hardness, 250-300 BHN, with a high speed steel slab type milling cutter, reductions in cutting forces up to 30% could be achieved over dry cutting. These results were achieved at a cutting speed of approximately 50 fpm and .011 feed per tooth. The most effective solid lubricant found under these conditions was potassium fluoborate (KBF_4).

Tool life tests conducted under the above conditions did not, however, indicate any truly significant increase in tool-life. It was felt that this was primarily due to the fact that the potassium fluoborate proved to be corrosive and could conceivably have contributed to an excessively high amount of corrosive wear. However, the fact that the cutting forces could be so significantly reduced indicates a possibility of success in the elevated temperature milling of these high strength, thermal resistant materials. It was felt that the significant reduction in cutting forces could contribute to less severe impact conditions when milling these high strength materials, and in so doing could possibly improve tool-life. Then too, the carbides should be more resistant to corrosive attack than was the high speed steel cutter.

Apparatus: The experimental studies were conducted on the face milling set-up used previously for elevated temperature face milling. A single tooth fly-cutter type face mill was used employing conventional throwaway carbide inserts. The tool material used throughout the tests was grade 370 carbide. The tool geometry employed consisted of -5° axial and radial rakes, 5° clearance, 15° corner angle, and a 1/32" corner radius. The work material used for these evaluations was Thermold J (460 BHN). The workpiece was heated by induction heating using a flat pancake type coil.

Essentially all of the solid lubricants found to be effective in reducing tool-chip interface friction in previous research were available in powder form. It was, therefore, decided to apply them directly to the cutter as it emerged from the cut once each revolution, with the simple compressed air powder atomizer, seen in Figure 60.

The compensated tool-work thermocouple was used to record tool-chip interface temperature on a cathode ray oscilloscope. The high stiffness milling dynamometer was used to measure impact forces during milling. The output from the strain gages was amplified and fed into an oscilloscope with high frequency response to allow accurate determination of these peak forces.

Results: A series of screening tests conducted under the above specified test conditions at room temperature and at 700°F, with and without lubricants yielded preliminary results which may be generalized upon as follows. Impact force was significantly reduced by the application of most of the solid lubricants evaluated. From Figure 61 it may be seen that at both room temperature and at 700°F impact forces were reduced in all cases except for the application of nickel sulfide at room temperature. Reductions in impact force as great as 30% were observed in the case of potassium fluoborate and ferrous sulfide at room temperatures. The reduction in forces for these two lubricants at elevated temperature was considerably less. In the instance where nickel sulfide was applied at room temperature, the impact force increased sharply, finish was poor and the material, as such, seemed to have a severe abrasive action on the cutting tool.

The tool-chip interface temperatures, as measured with the tool-work thermocouple, were reduced by the application of the lubricants. This may be seen from Figure 62. Here again, the only exception was that instance where nickel sulfide was used as the lubricant at room temperature. Here, interface temperature appeared to increase slightly over that obtained when milling dry. The tool-chip interface temperature may be seen to increase in all instances when milling at the elevated workpiece temperature of 700°F, as compared to milling at room temperature, as great as the increase in workpiece temperature. This was undoubtedly due to the reduction in shear strength of the work material at this elevated temperature. The amount of metal removed was insufficient to determine trends in tool wear rates.

Figure 63 summarizes the results of the two preceding figures and shows the possible improvements that may be obtained with each material. The melting temperature is compared with the interface temperature. When the melting point is exceeded, the materials no longer behave as solid films but appear as liquid films.

On the basis of the above screening tests, it may be concluded that the potassium fluoborate and the ferrous sulfide were the two lubricants indicating most promise. The ferrous chloride and magnesium chloride were both found to be hygroscopic, making them difficult to handle in the atomizer. Corrosion of the machine tool and surrounding fixtures by the lubricants was experienced, except in the case of the molybdenum disulfide.

A second series of tests were conducted in order to evaluate tool life obtained utilizing the following lubricants: potassium fluoborate, molybdenum disulfide, steam, carbon tetrachloride applied in combination with steam as a carrier, and under conditions of dry cutting. The tool geometry remained unchanged as did the 370 grade of carbide. Tool wear curves were plotted as may be seen in Figure 64. Here, it may be noted that the lowest rate of wear was achieved with the cutting tool performing without lubricant. The potassium fluoborate on the other hand, which indicated the greatest ability to reduce cutting forces, gave the highest rate of tool wear.

The fact that throughout this investigation a number of these lubricants indicated the capability of reducing cutting forces and yet resulted in a greater rate of tool wear leads one to believe that the corrosive attack due to these lubricants has, in effect, accelerated the rate of tool wear. The condition of the cutting edge at the point of .015" flank wear are indicated in Figure 65. The elapsed time to a value of .015" flank wear is given for each cutting condition.

Summary: In summarizing the results of this investigation to examine the possibility of effecting improved performance through the utilization of a metal cutting lubricant, the following stagements may be made. Under the conditions investigated here, the application of dry lubricants to the milling process did not contribute to increased tool life. A number of the lubricants, however, did effectively reduce impact forces so long as the tool remained relatively sharp. Tool-chip interface temperatures were also reduced through the use of these lubricants. Evidence indicates that corrosive attack by the lubricant on the cutting tool may have been a factor adversely affecting their performance. In spite of what might at first appear to be negative results, the fact still remains that lubricants did reduce the impact forces and cutting temperatures. It is not impractical then to imagine that if the cutting conditions were such that tools did not chip, and if an effective lubricant could be found which was not corrosive to the tool some beneficial results might yet be achieved.

Asbestos as a Metal Cutting Lubricant

Introduction: Early in the investigation of elevated temperature machining, an attempt was made to conserve the heat in the workpiece by lagging it with asbestos sheet. By placing about 3/8" thickness of crysotile asbestos at entry to the cut, as shown in Figure 66, it was found that tool life could be greatly prolonged under certain cutting conditions. Figure 67 shows how it enabled greater tool life to be obtained in cutting 360 BHN 17-4 MO stainless steel at positive and highly negative angles of engagement. Comparison of Figure 41 with Figure 68 shows how, for 390 BHN AISI 4340 and Thermold J and 360 BHN 17-7 PH, improvement in tool life resulted under all of the conditions tried when asbestos was used. It was felt that these improvements were effected by three contributing conditions: "(a) a thermal effect due to the insulation protection afforded by the asbestos raising the engagement surface temperature by about 10% over the surface allowed to radiate in air; (b) a possible chemical effect in which the asbestos chemically reacts with tool or work material and behave- as a cutting lubricant at the chip-tool interface. The asbestos used was Canadian crysotile, which is a hydrated silicate of magnesium, and traces of chemical compounds of magnesium, silicon and H_2O were found on the carbide tip after cutting by x-ray diffraction and emission spectroscopy methods; and (c) a dynamic effect where the asbestos provides a damping effect reducing the severity of the impact of cutter on workpiece during the intermittent cut."

Experimental Work: After the use of asbestos doubled and tripled the tool life of the nickel and cobalt base alloys, it was felt that further work should be carried out to determine the reasons for this phenomenon.

To determine if the major reason for the increased tool life was the thermal effect due to the insulation increasing the entry temperature and decreasing the entry strength, temperature measurements on the side of the workpiece were taken. A thermocouple was welded to the workpiece on the entry side approximately 1/8 inch from the top. The temperature was measured just as the cutter sheared off the thermocouple with and without asbestos sheets covering the surface.

The surface temperature was lower when the asbestos was used. This was due to the fact that the asbestos prevented the "flame splash" from the arc from playing against this surface. When other heating methods, such as induction heating, are used the entry surface will be maintained at a higher temperature but this does not appear to be a major factor.

To determine if this increase could be obtained only at elevated temperatures, tests were run at room temperature. The use of asbestos increased the tool life nine-fold! This indicated that the effect was preimarily due to a reduction in impact and/or chemical lubrication.

To measure the impact forces, an accelerometer was mounted on the rear of one of the cutting tools as shown in Figure 69. The signal was led through the spindle to the mercury pot. It was taken from the mercury pot through a cathode follower and preamplifier to a high speed oscilloscope seen in Figure 70. Pictures were taken of the oscilloscope trace to compare the values. These photographs were not reproducible, but Figure 71 depicts typical traces obtained.

A comparison of the impact values obtained under different conditions when face milling Haynes Alloy No. 25 and based on the impact force at room temperature defined as 100% the following values were obtained:

Room temperature (no asbestos) 100%
Room temperature (asbestos) 91.9%
850°F (no asbestos) 58.5%
850°F (asbestos) 45.8%.

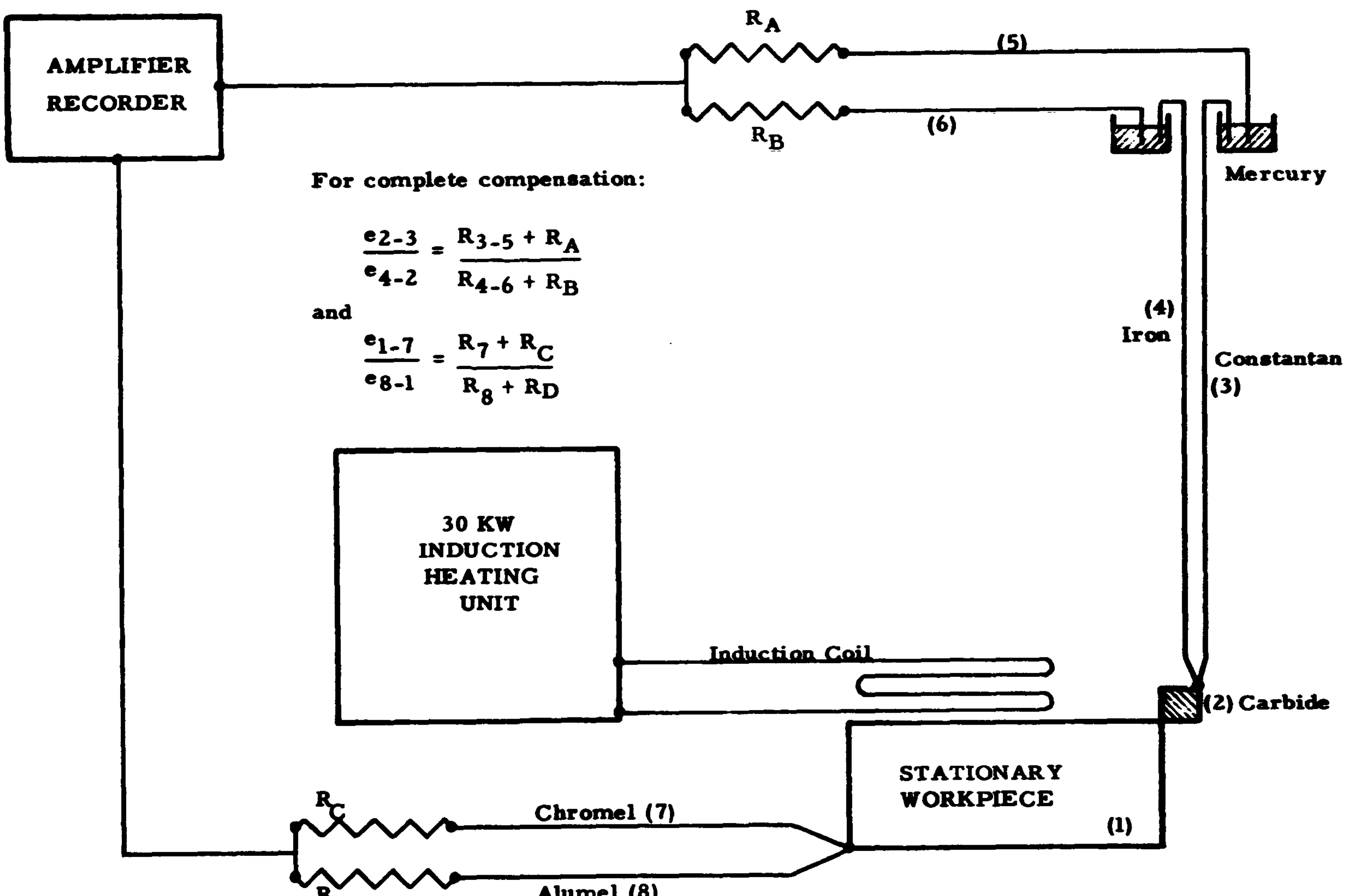
Measurements of the impact forces obtained when velumoid (a gasket material), aluminum, and rubber were placed at the entry showed that the impact force was again reduced about 10% although tool life was not increased significantly.

Consequently, it was felt that impact forces did not play an important part and a variety of materials were tried to isolate the chemical effect. The results of these tests are given in Figure 72.

In this figure it may be seen that each of the materials that contain a large amount of silicon give a significant increase in tool life.

It is felt that the primary mechanism of the increased tool life is the presence of a film of silicon-containing material at the chip-tool interface. This is also borne out by spectrographic analysis which shows that silicon is distributed over the face of the chip.

DOUBLE COMPENSATED TOOL-WORK THERMOCOUPLE CIRCUIT
(INDUCTION HEATING SET-UP)



For complete compensation:

$$\frac{e_{2-3}}{e_{4-2}} = \frac{R_{3-5} + R_A}{R_{4-6} + R_B}$$

and

$$\frac{e_{1-7}}{e_{8-1}} = \frac{R_7 + R_C}{R_8 + R_D}$$

FIGURE 37

THREE AXES MILLING DYNAMOMETER

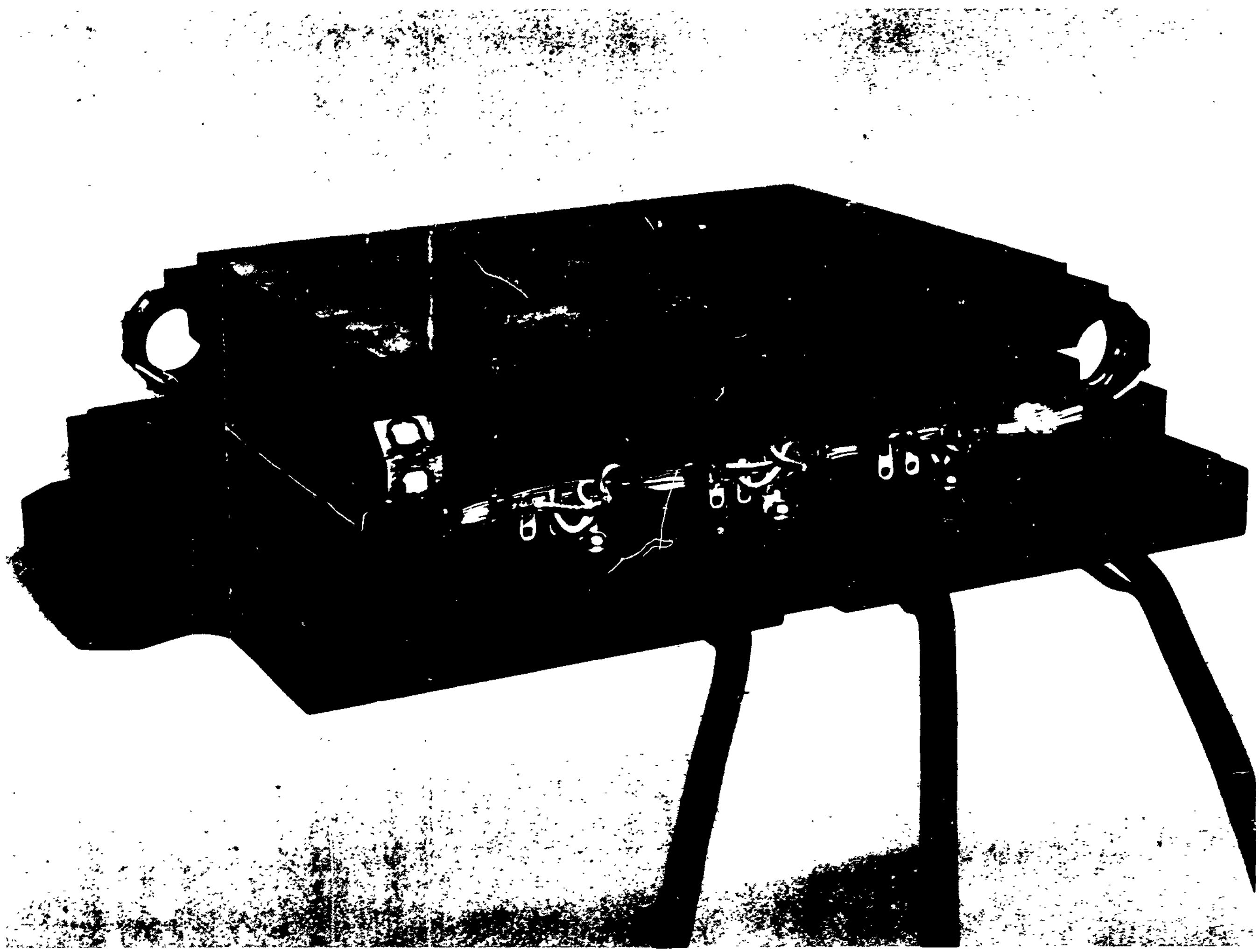


FIGURE 38

TYPICAL TOOL-LIFE/CUTTING SPEED CURVES AT VARIOUS TEMPERATURES

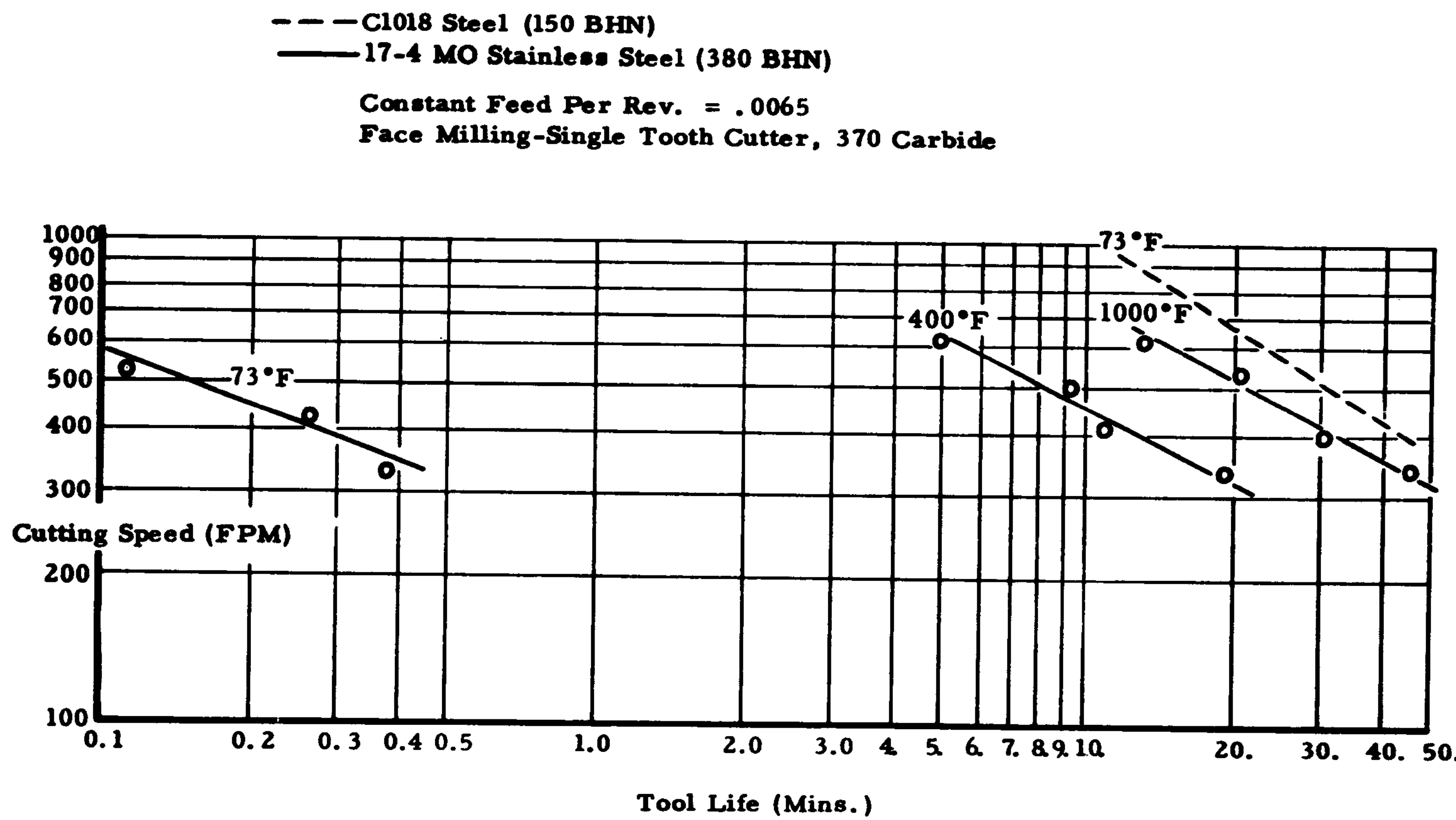


FIGURE 39

TYPICAL TOOL-LIFE/CUT SPEED CURVES AT VARIOUS TEMPERATURES

- - - C1018 Steel (150 BHN)
—— Thermold J Die Steel (390 BHN)

Constant Feed Per Rev. = .0065
Face Milling-Single Tooth Cutter, 370 Carbide

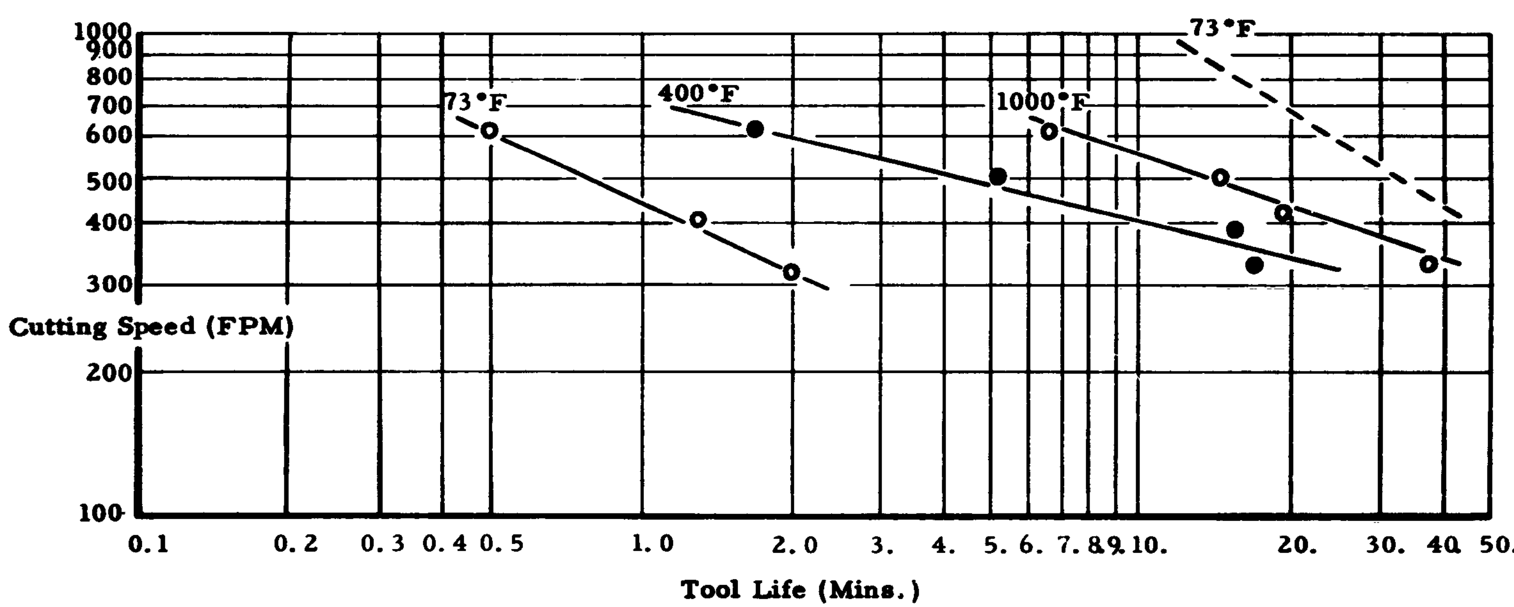


FIGURE 40

EFFECTS OF ENGAGEMENT ANGLE IN HOT MACHINING
FACE MILLING OPERATION

Work Material: See Below
Tool Material: 370 Carbide
Cut Speed: 512 FPM, .0058 IPR

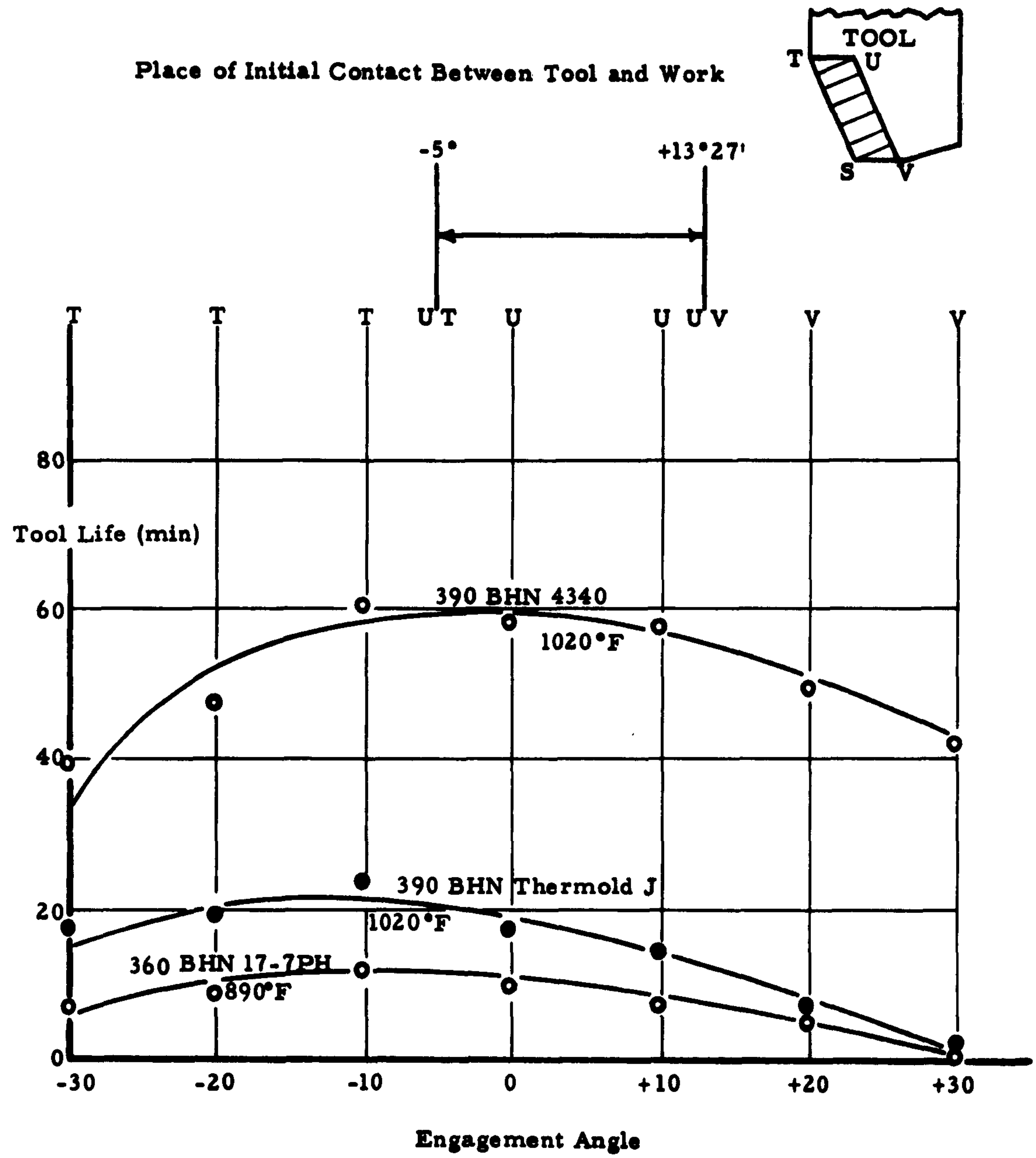
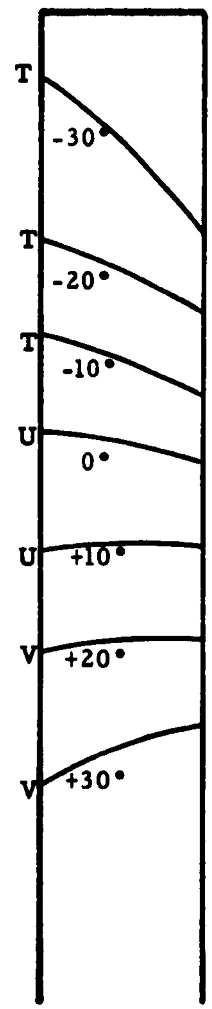


FIGURE 41

PATHS OF CUTTING AND TYPE OF CONTACT FOR VARIOUS ENGAGEMENT ANGLES

3" Radius Cutter
1" Wide Workpiece



(Letters refer to Figure 42)

FIGURE 42

EFFECT OF TOOL MATERIALS ON TOOL WEAR IN HOT MILLING
FACE MILLING OF 500 BHN THERMOLD J

Cutting Speed: 525 FPM
Feed: .0061 IPT
Depth of Cut: 1/8"
Workpiece Temperature: 950°F

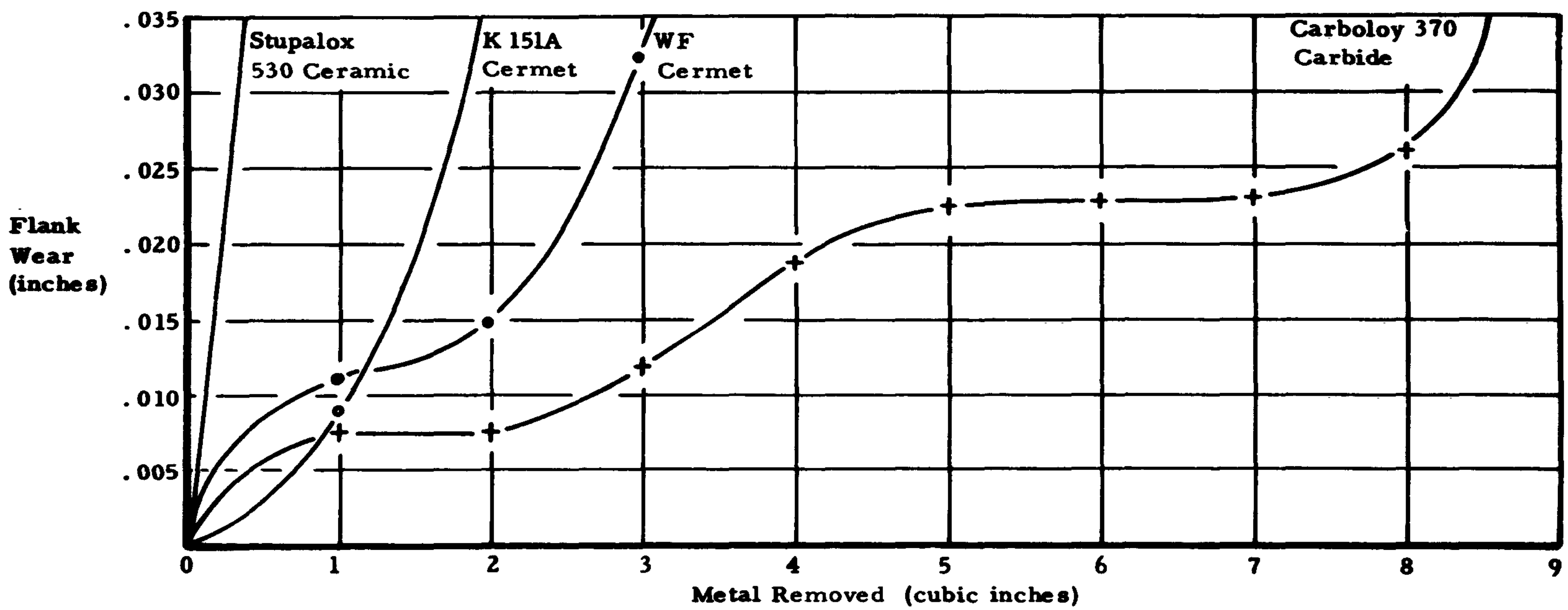


FIGURE 43

EFFECT OF TOOL GEOMETRY ON TOOL LIFE IN HOT FACE MILLING
WORKPIECE TEMPERATURE 950°F
Cutting Speed: 525 FPM, Feed: .0061 IPT, Depth Cut: 1/8"

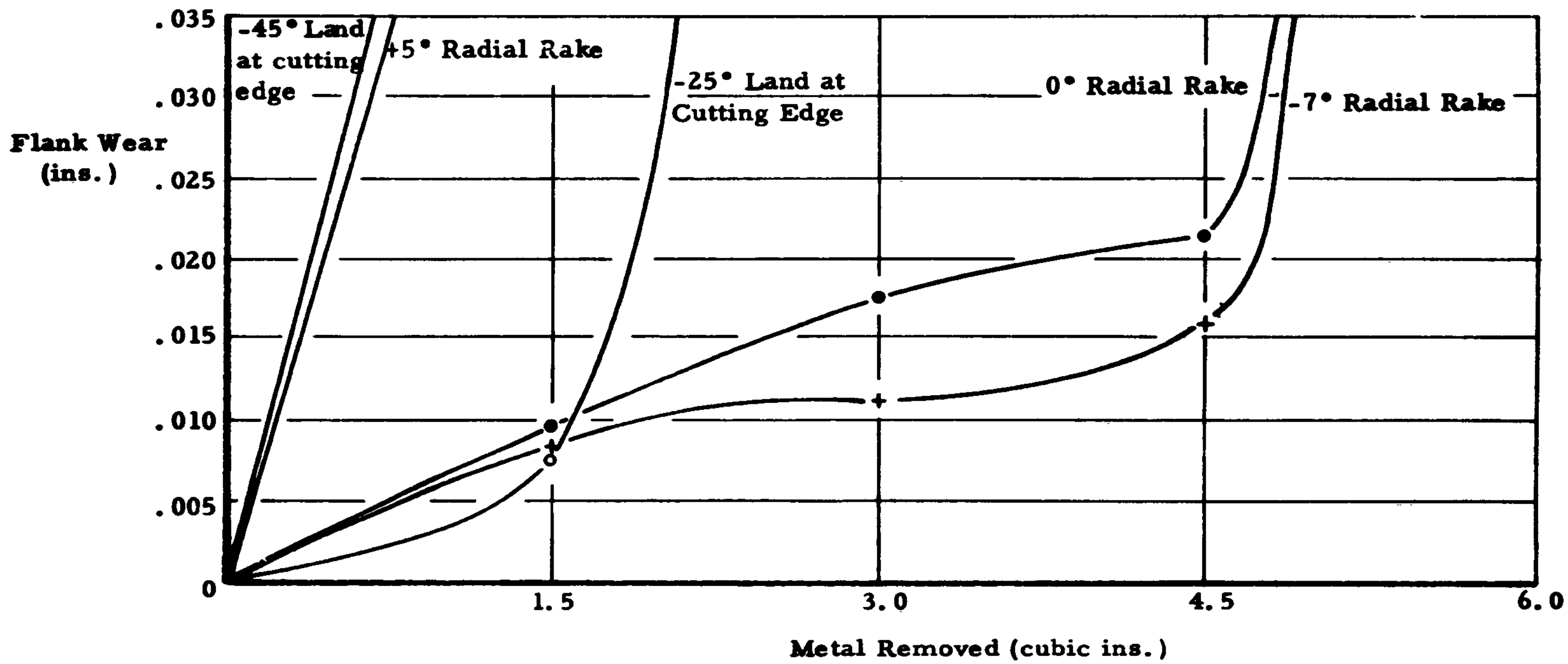


FIGURE 44

PLOT OF TOOL LIFE VS. AVERAGE TOOL TEMPERATURE IN HOT MILLING OF 380 BHN 17-4 Mo STAINLESS

Points shown were obtained at four cutting speeds: ▲ 343 FPM, o 412 FPM, + 525 FPM, ● 624 FPM, and at Workpiece temperatures varying from 240°F to 1050°F.
Tool Material: 370 Carbide

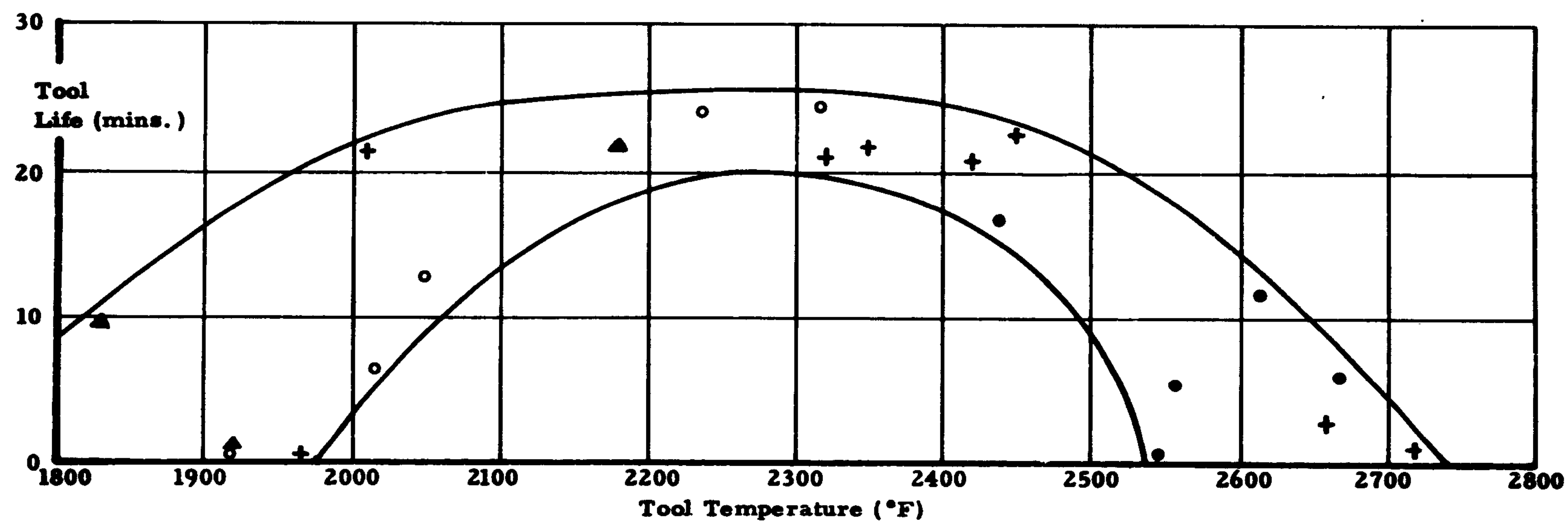


FIGURE 45

EFFECT OF TEMPERATURE ON TOOL LIFE MILLING RENE' 41

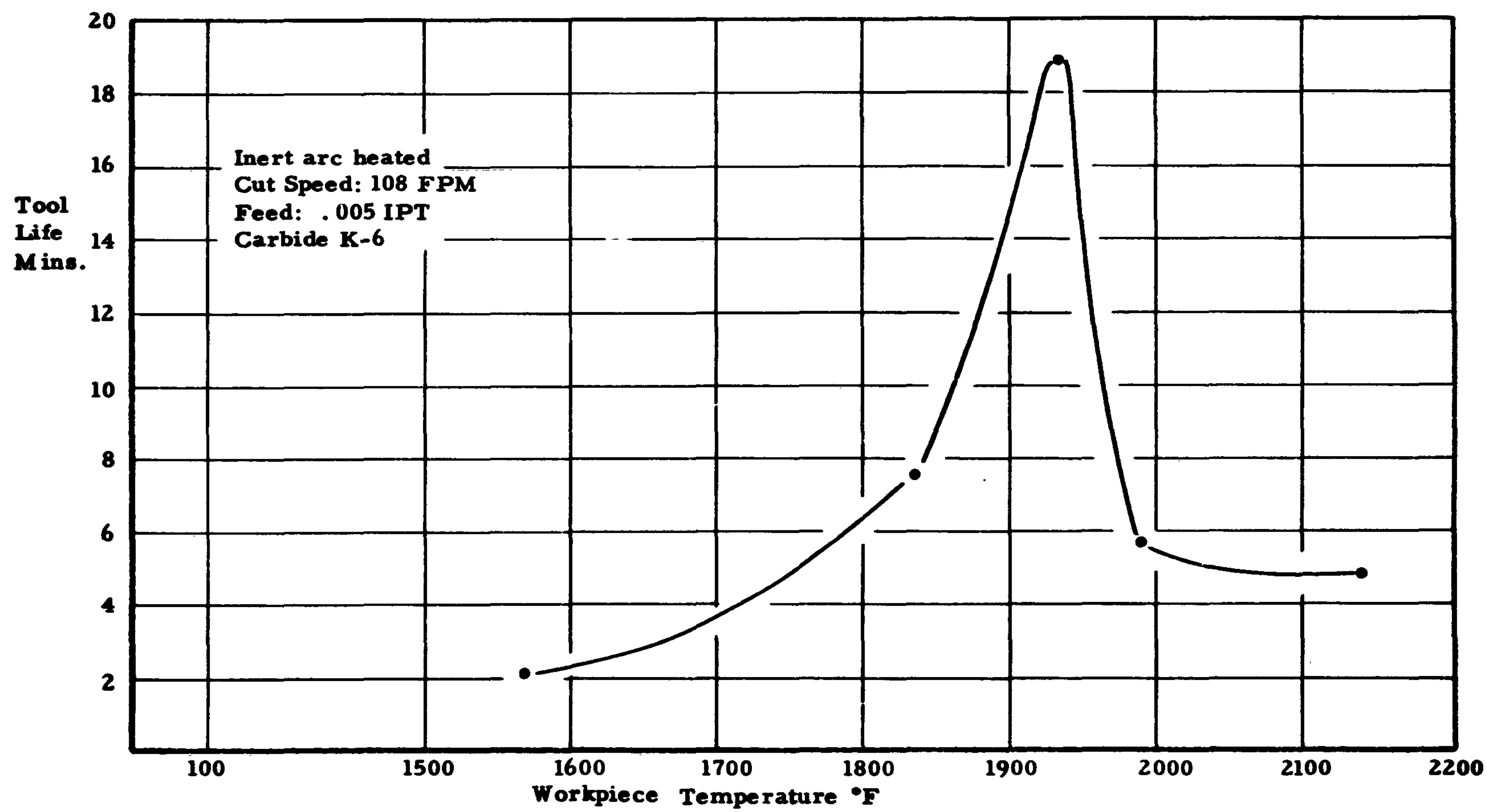


FIGURE 46

TOOL LIFE VS. CUTTING SPEED FACE MILLING
RENE' 41 AT ROOM AND AN OPTIMUM TEMPERATURE

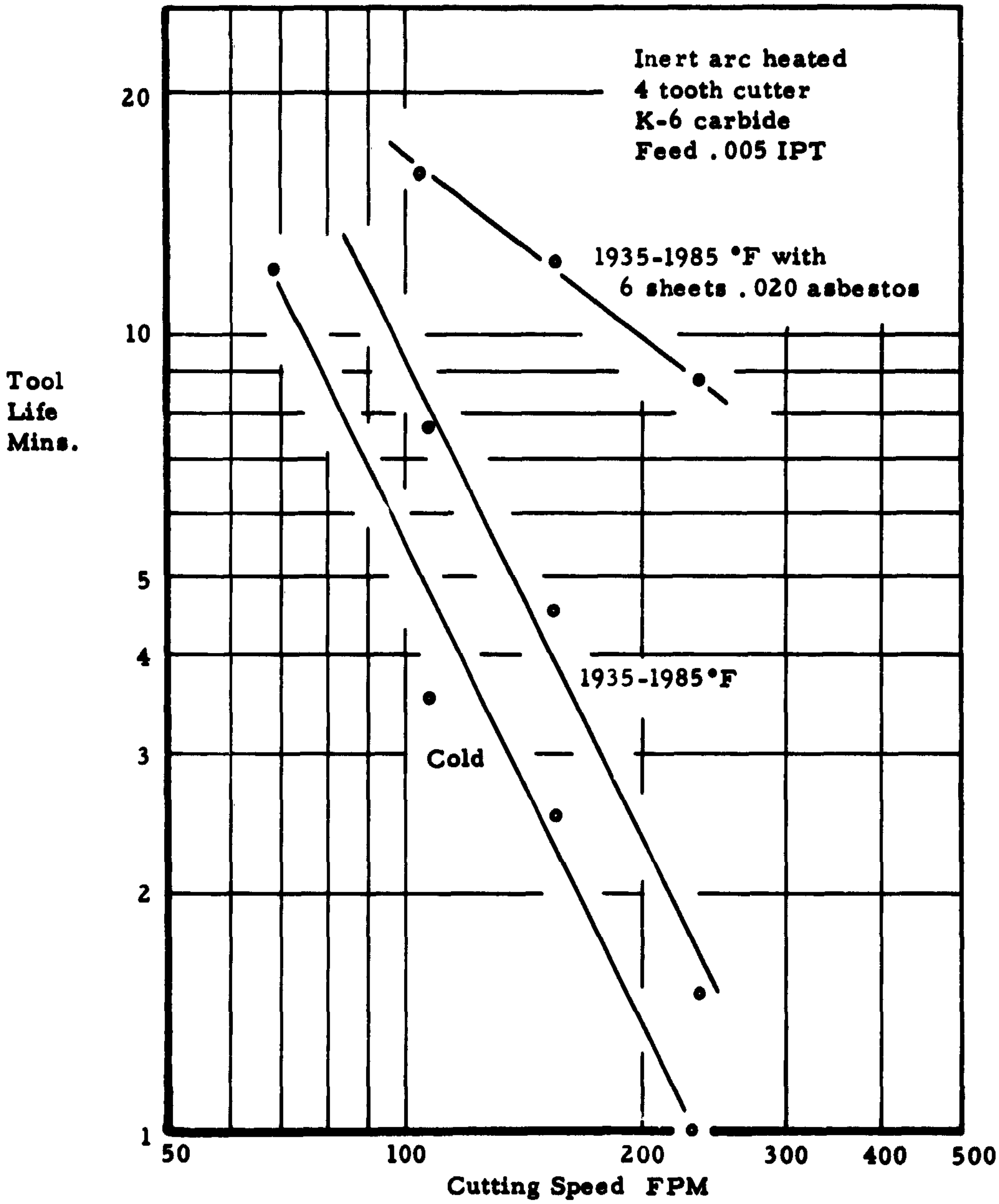


FIGURE 47

EFFECT OF TEMPERATURE ON TOOL LIFE MILLING HAYNES 25

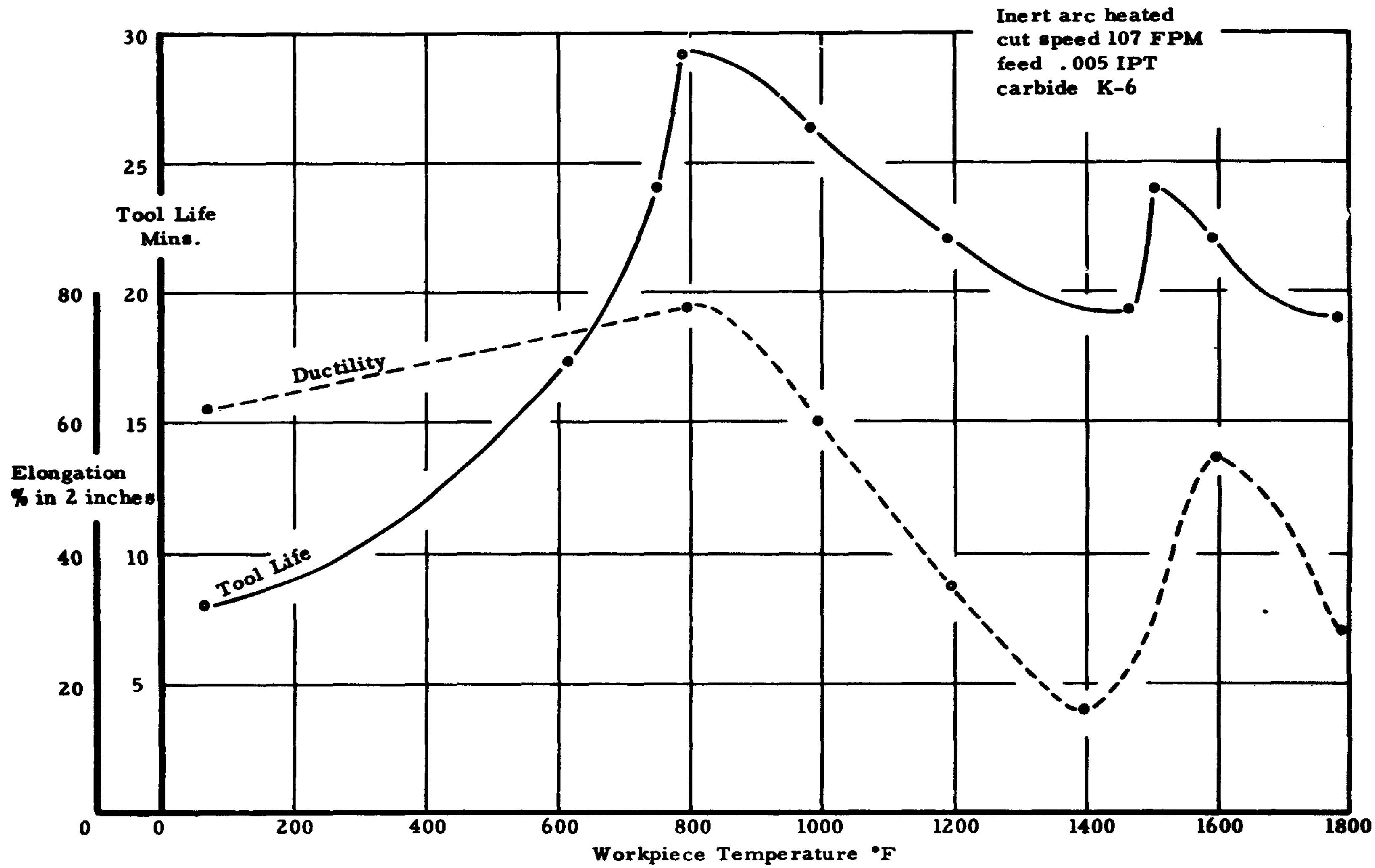


FIGURE 48

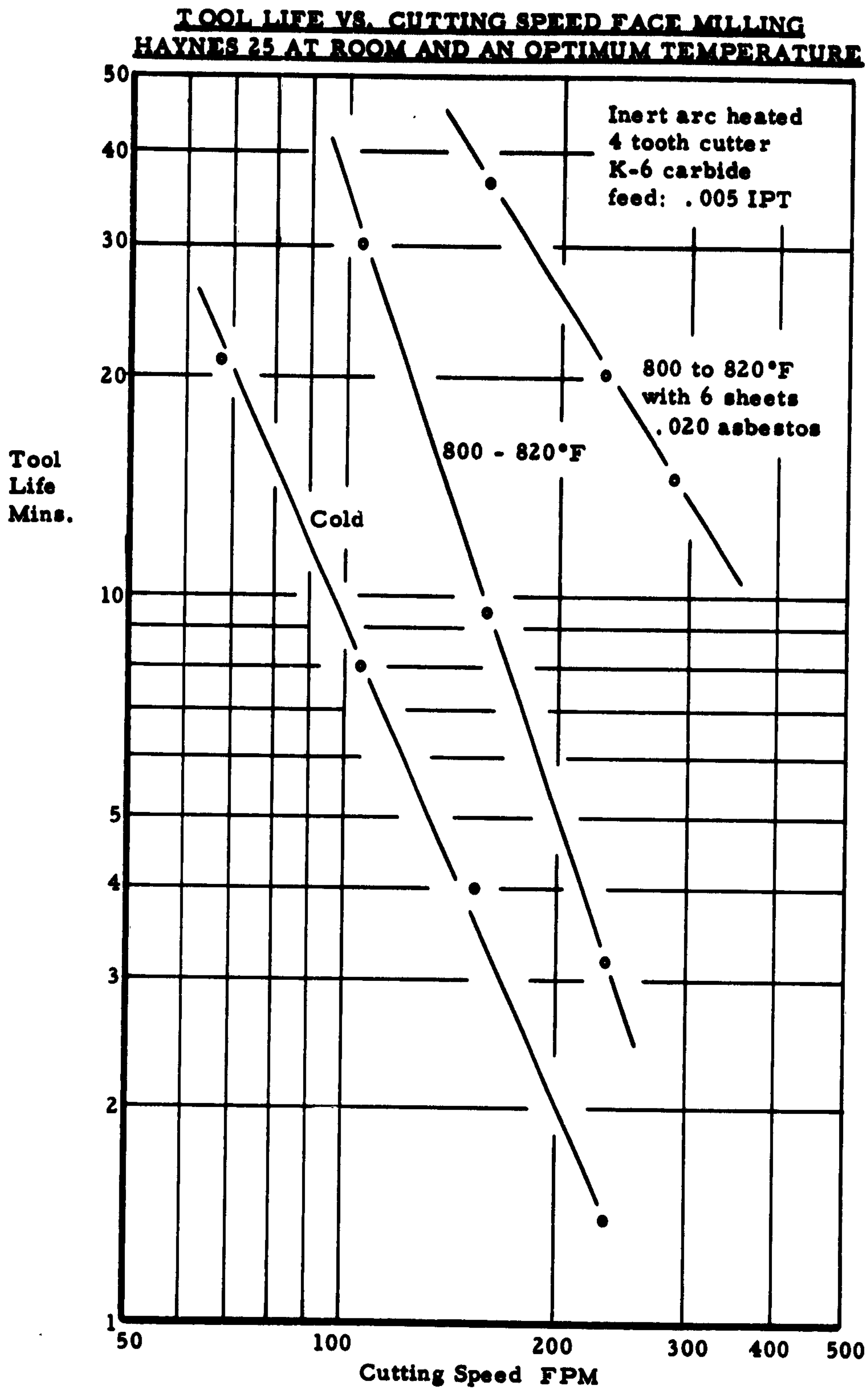

TOOL LIFE VS. CUTTING SPEED FACE MILLING
HAYNES 25 AT ROOM AND AN OPTIMUM TEMPERATURE
Inert arc heated
4 tooth cutter
K-6 carbide
feed: .005 IPT
800 to 820°F
with 6 sheets
.020 asbestos
800 - 820°F
Cold
Tool
Life
Mins.
50
40
30
20
10
5
4
3
2
1
50
100
200
300
400
500
Cutting Speed FPM

FIGURE 49

EFFECT OF TEMPERATURE ON TOOL LIFE MILLING INCONEL X

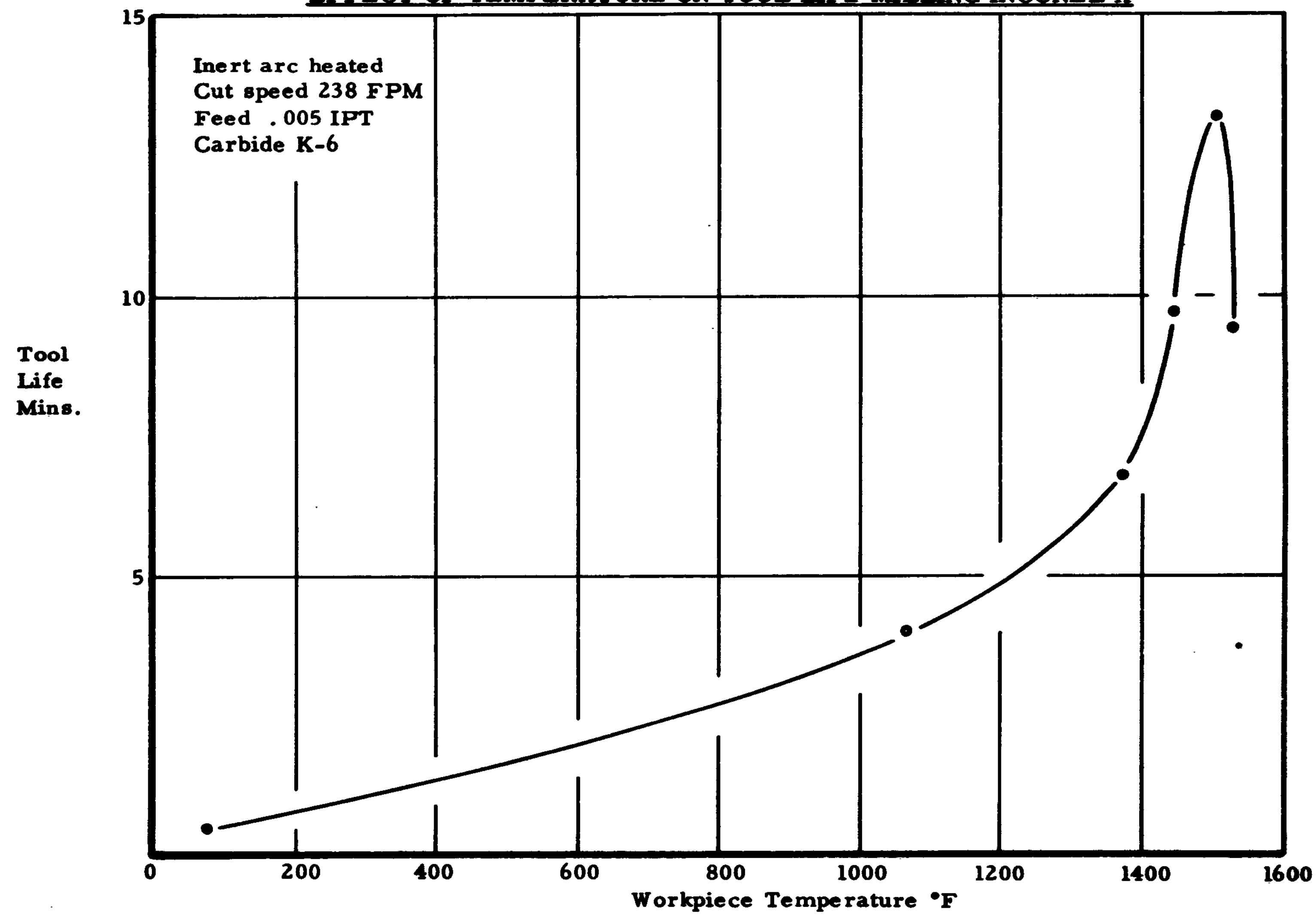


FIGURE 50

TOOL LIFE VS. CUTTING SPEED FACE MILLING INCONEL X AT ROOM AND AN OPTIMUM TEMPERATURE

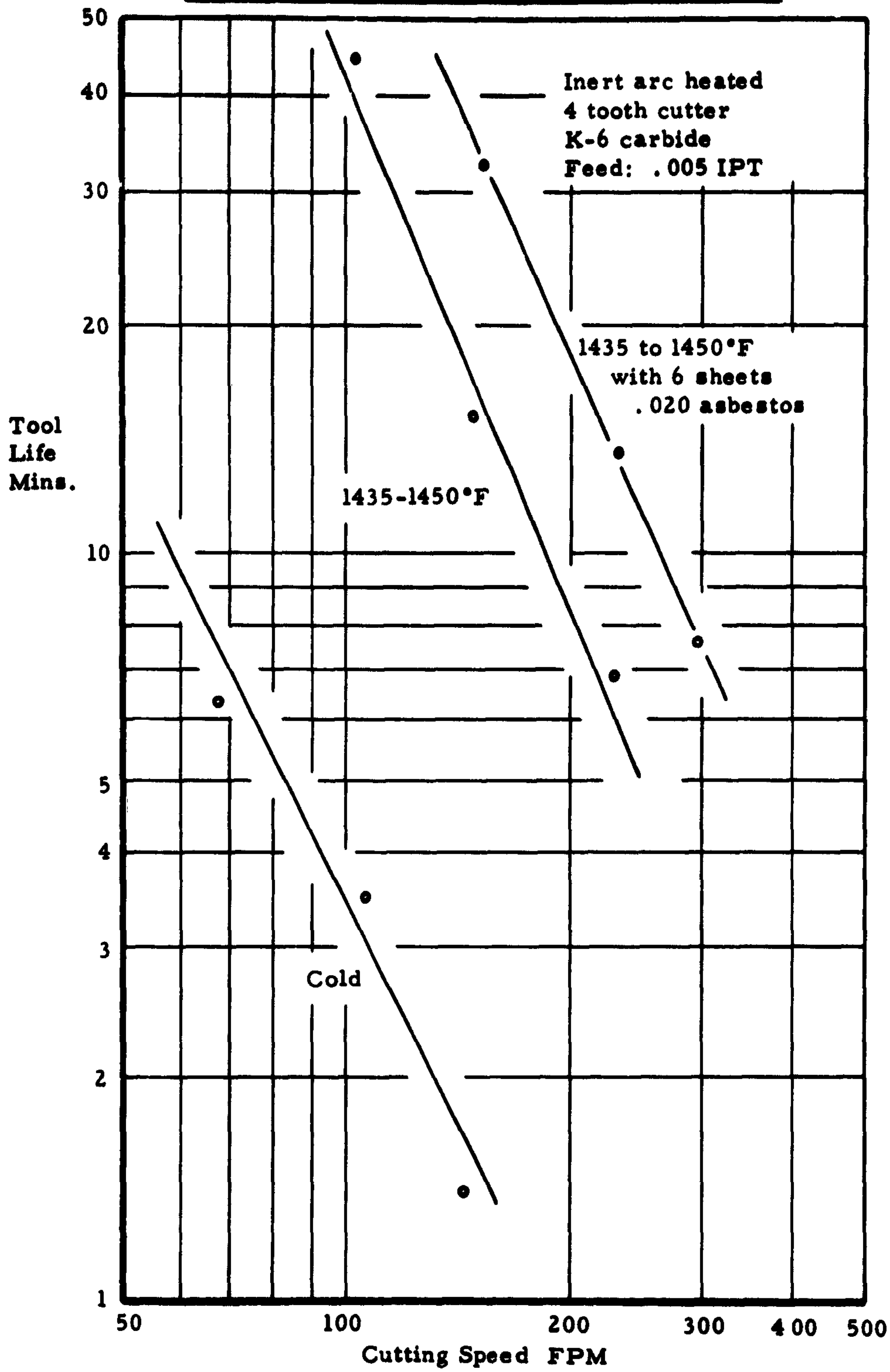


FIGURE 51

TYPICAL WEAR WHEN FACE MILLING RENE' 41

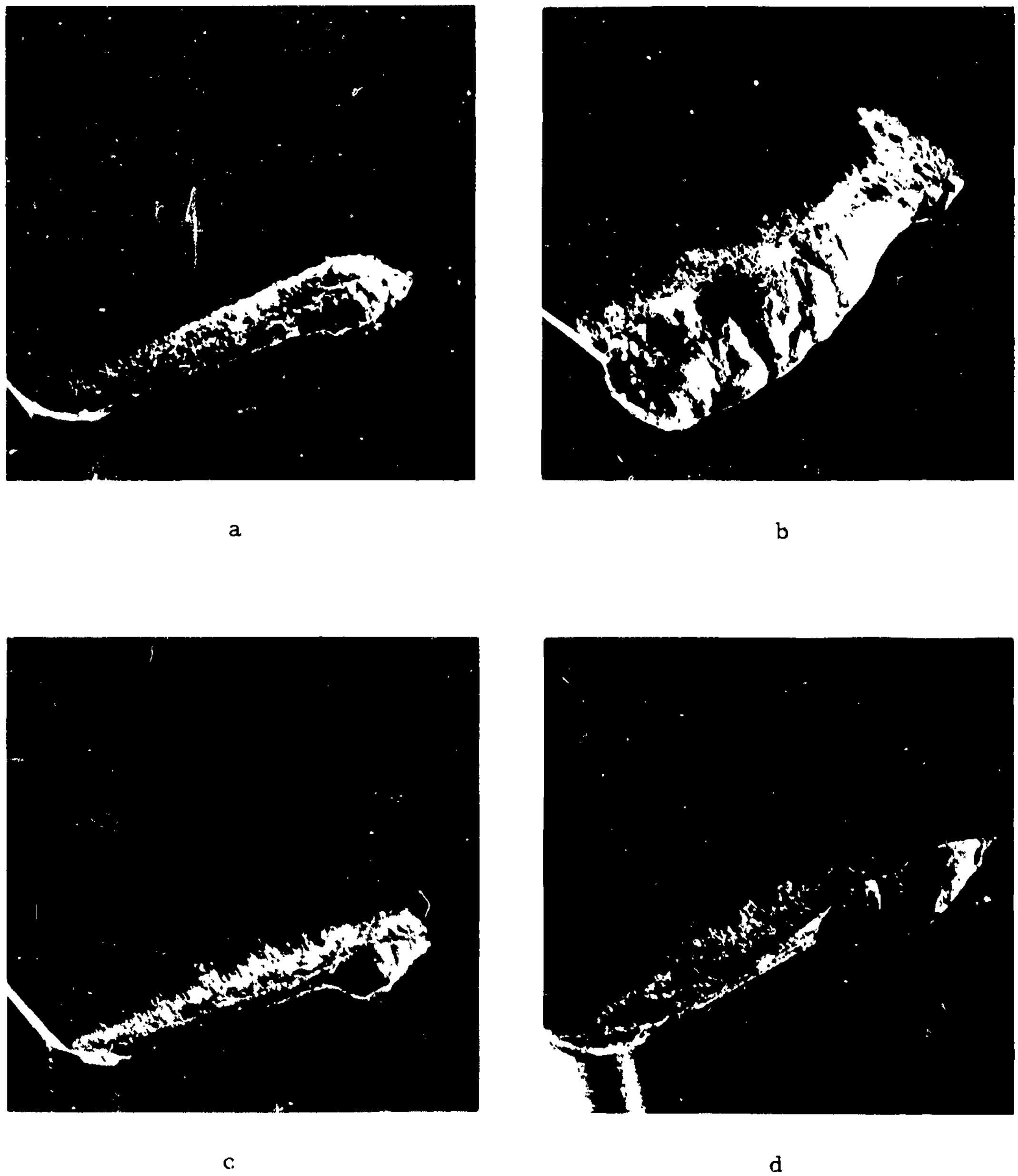


FIGURE 52

TOOL LIFE VS. CUTTING SPEED FACE MILLING RENE' 41

at Room and Elevated Temperature
4 inch wide solution treated and aged work
0° Radial Rake +7° Axial Rake

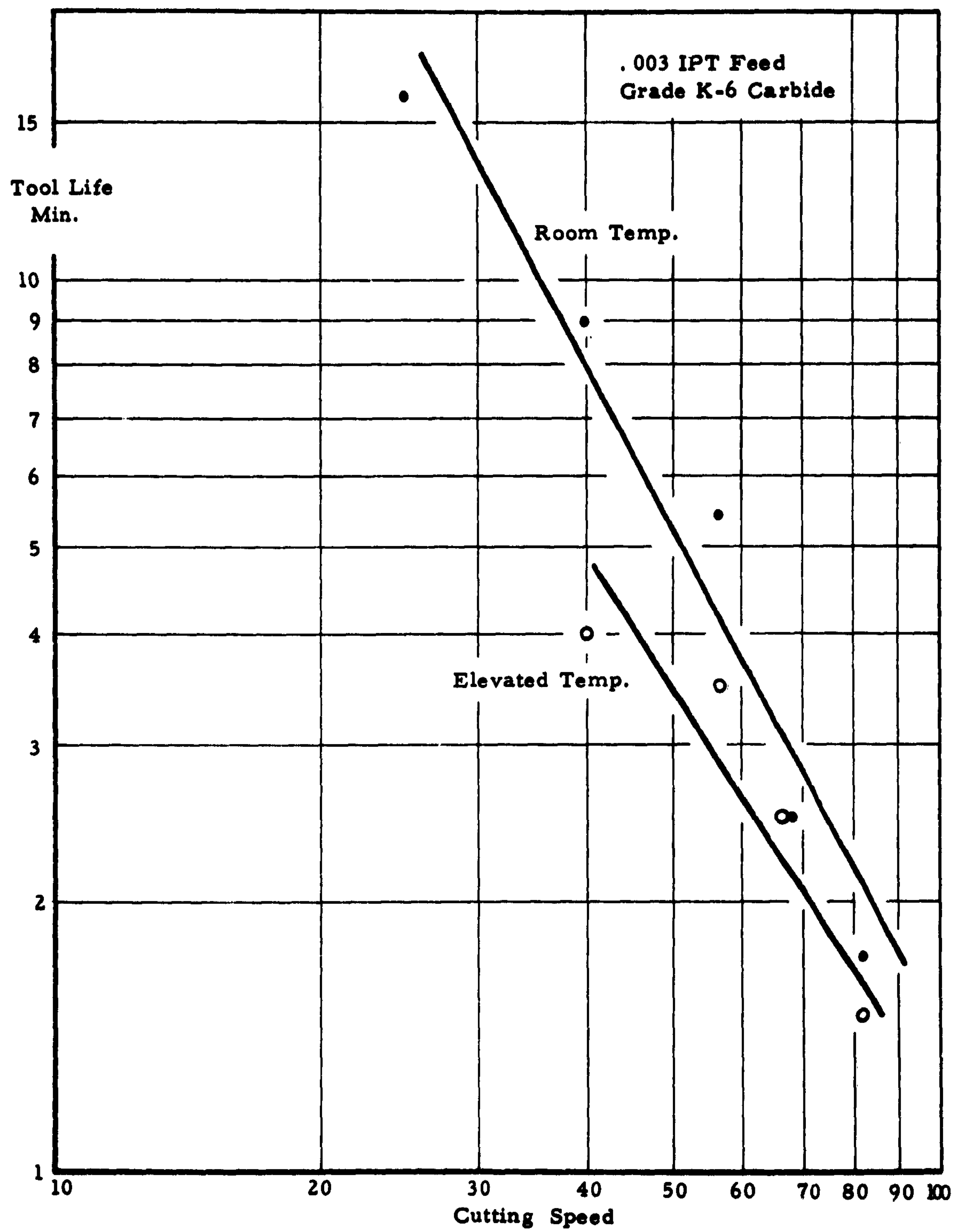


FIGURE 53

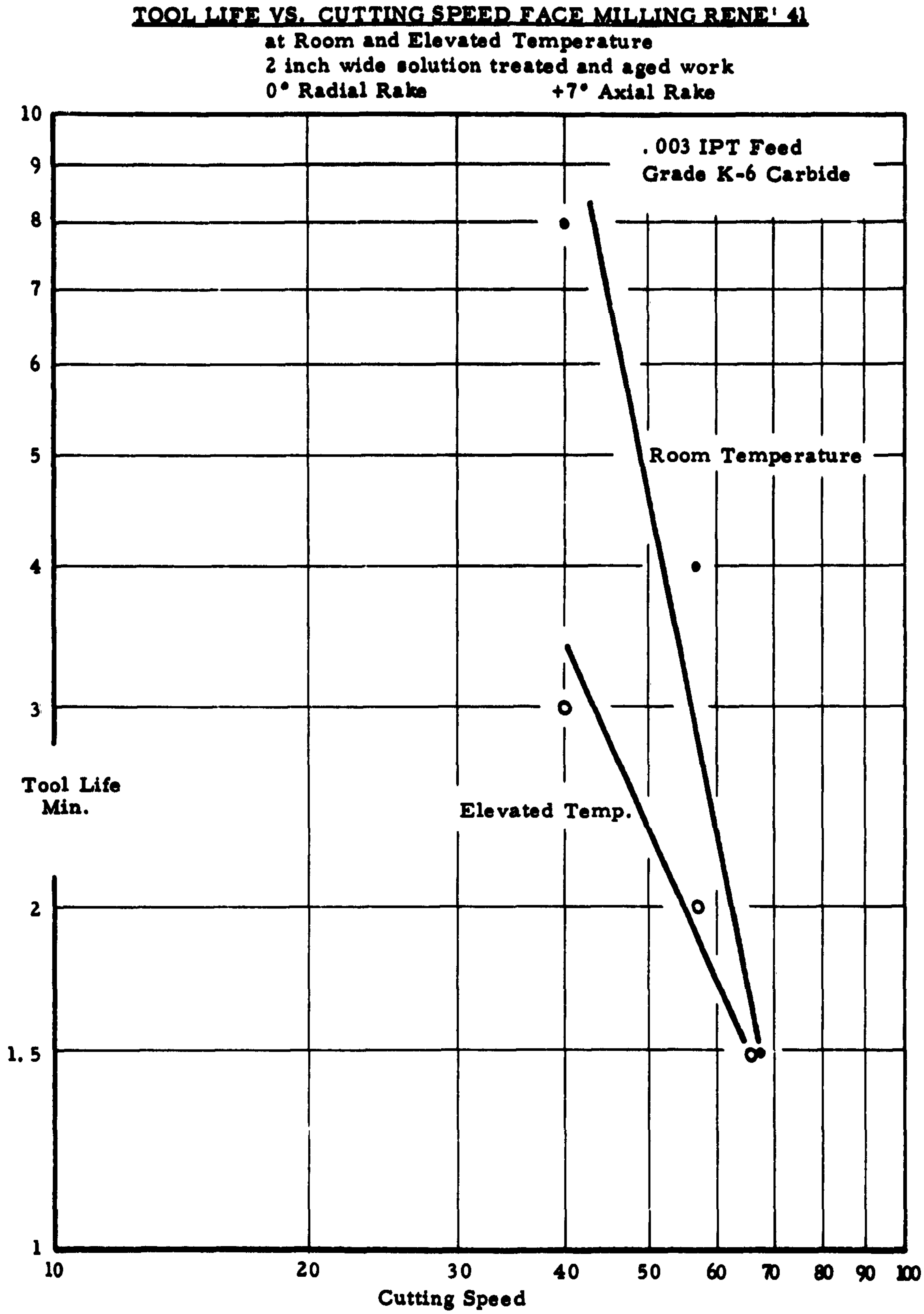
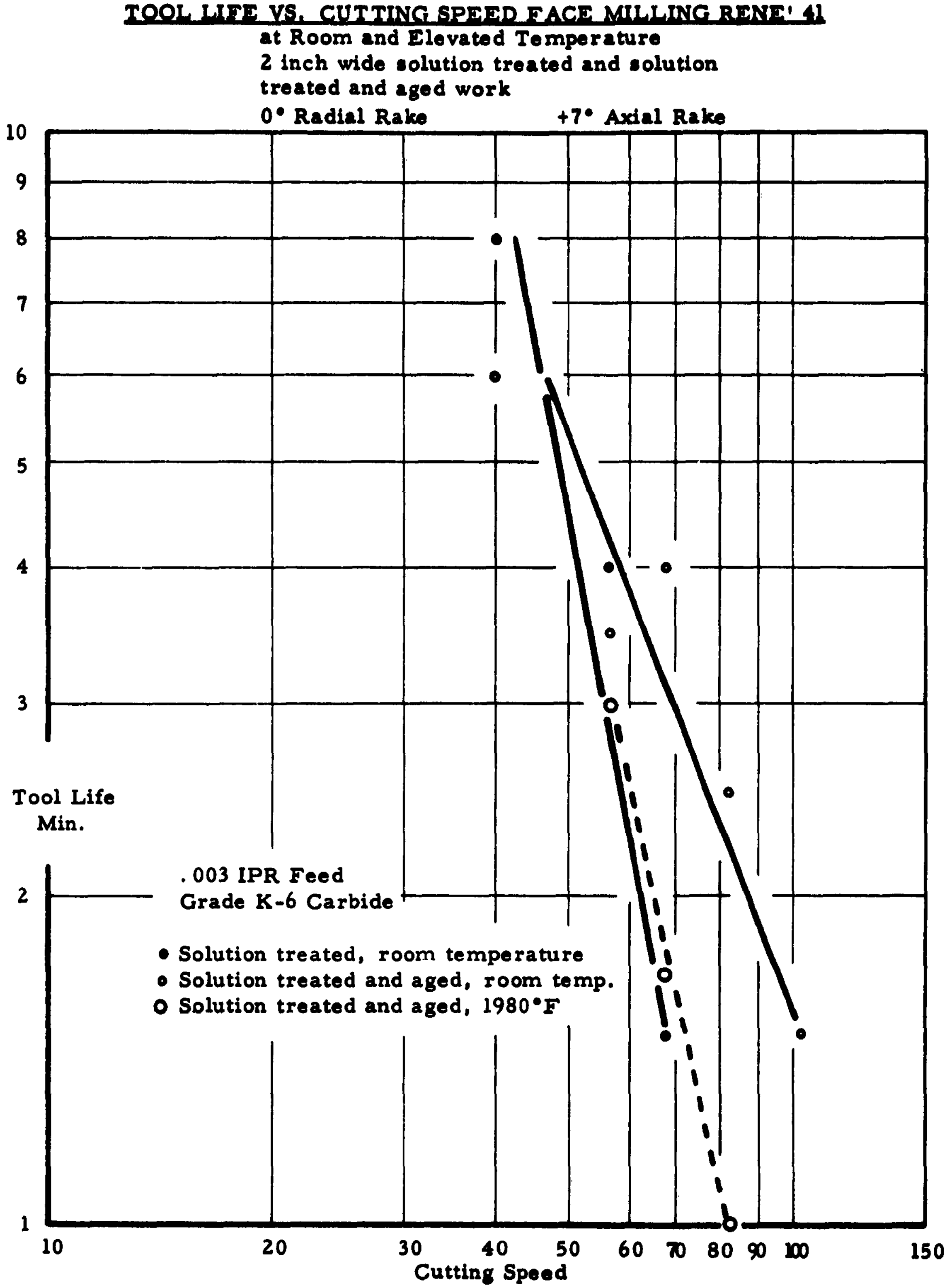

TOOL LIFE VS. CUTTING SPEED FACE MILLING RENE' 41
at Room and Elevated Temperature
2 inch wide solution treated and aged work
0° Radial Rake
+7° Axial Rake
.003 IPT Feed
Grade K-6 Carbide
Room Temperature
Elevated Temp.
Tool Life
Min.
Cutting Speed
10
9
8
7
6
5
4
3
2
1.5
1
10
20
30
40
50
60
70
80
90
100

FIGURE 54



TOOL LIFE VS. CUTTING SPEED FACE MILLING RENE' 41
at Room and Elevated Temperature
2 inch wide solution treated and solution treated and aged work
0° Radial Rake
+7° Axial Rake
10
9
8
7
6
5
4
3
2
1
Tool Life Min.
.003 IPR Feed
Grade K-6 Carbide
Solution treated, room temperature
Solution treated and aged, room temp.
Solution treated and aged, 1980°F
10
20
30
40
50
60
70
80
90
100
150
Cutting Speed

FIGURE 55

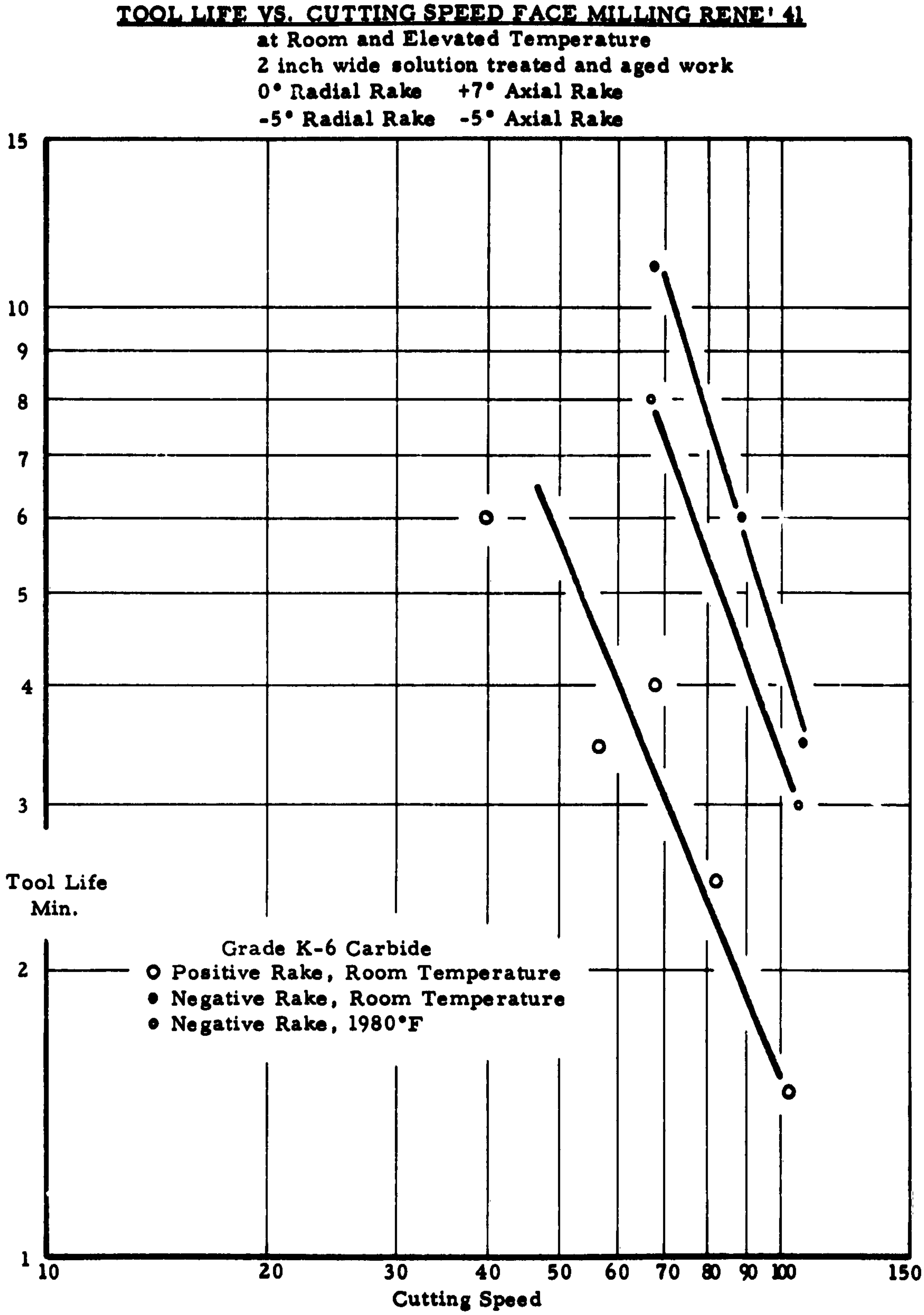

TOOL LIFE VS. CUTTING SPEED FACE MILLING RENE' 41
at Room and Elevated Temperature
2 inch wide solution treated and aged work
0° Radial Rake +7° Axial Rake
-5° Radial Rake -5° Axial Rake
15
10
9
8
7
6
5
4
3
2
1
Tool Life
Min.
Grade K-6 Carbide
Positive Rake, Room Temperature
Negative Rake, Room Temperature
Negative Rake, 1980°F
10
20
30
40
50
60
70
80
90
100
150
Cutting Speed

FIGURE 56

TOOL LIFE VS. WIDTH OF RENE' 41 WORKPIECE
at Room and Elevated Temperature

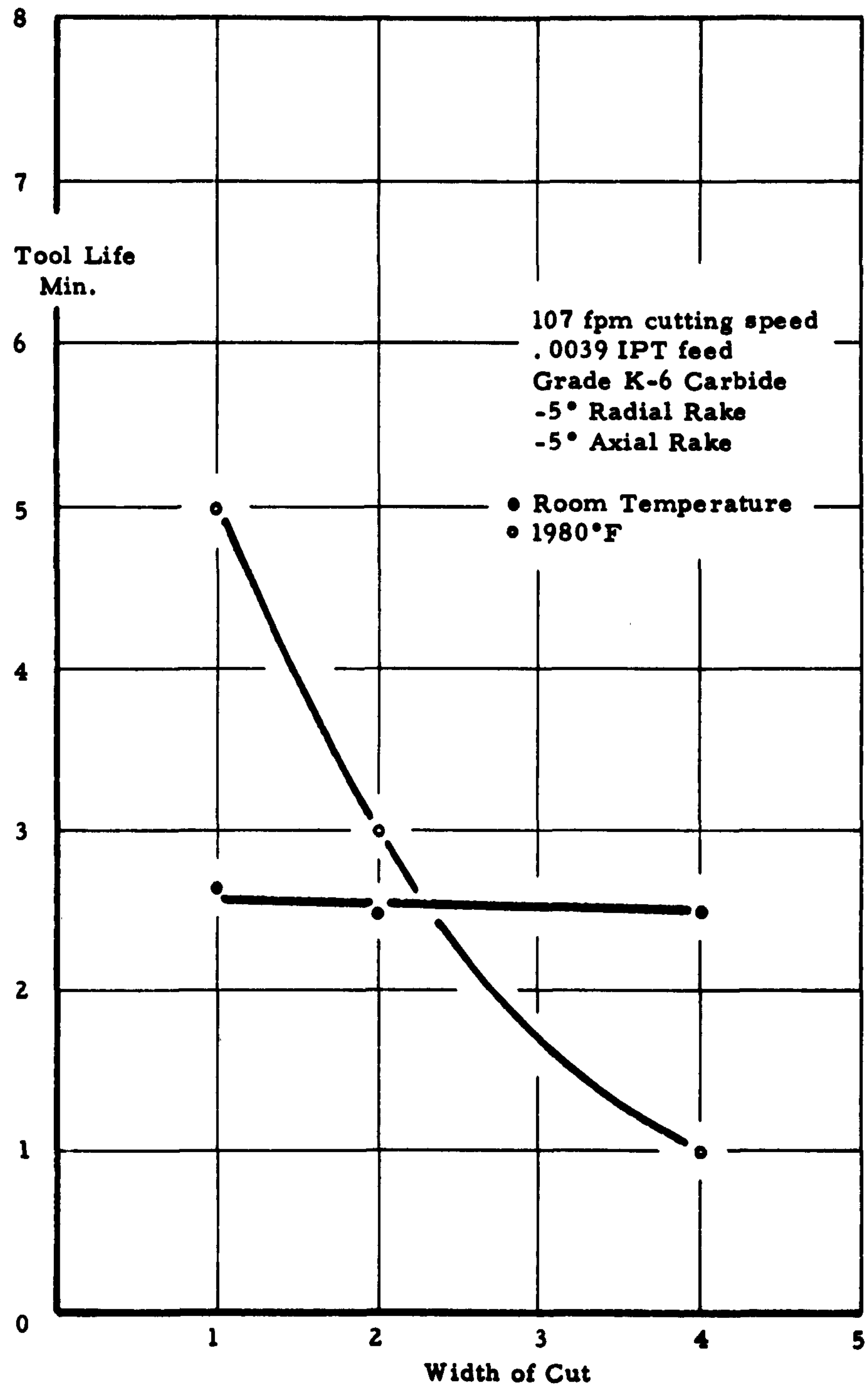


FIGURE 57

INERT ARC HEATING ON THE LATHE

Tool, Workpiece, Torch, Copper Brush

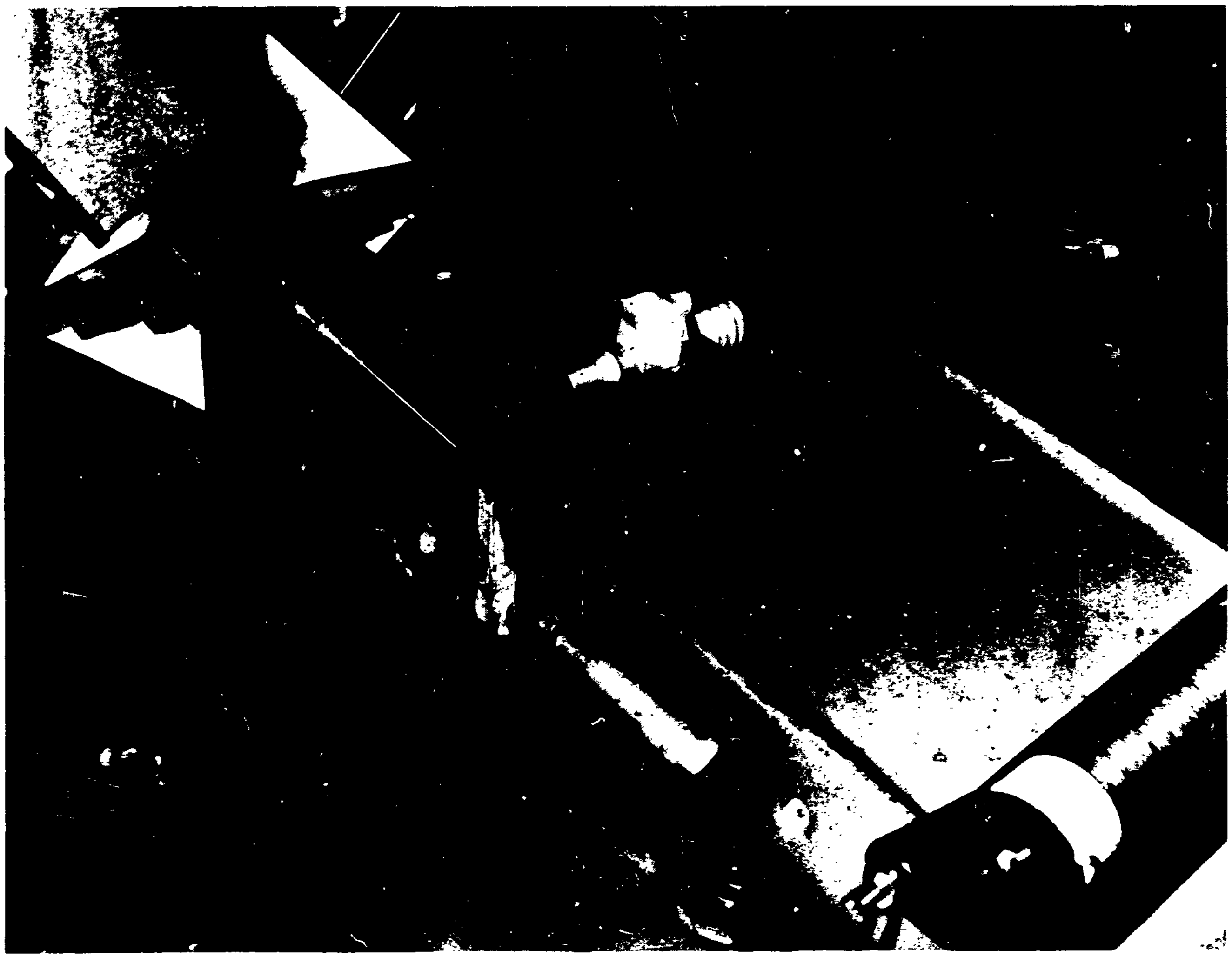


FIGURE 58

ORTHOGONAL CUTTING

EFFECT OF CHIP THICKNESS ON SHEAR PLANE ANGLE AND LENGTH OF SHEAR PATH

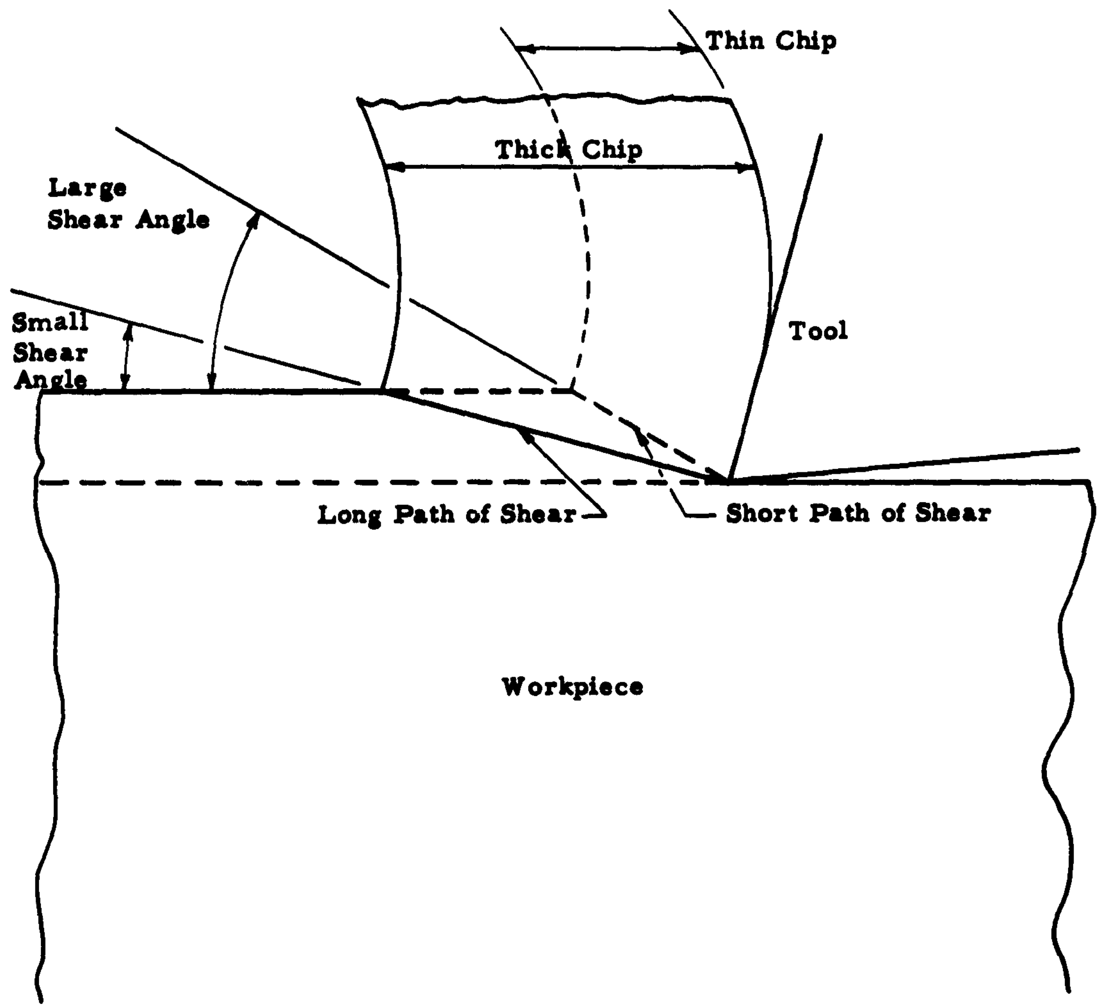


FIGURE 59

HOT MILLING WITH LUBRICANTS

Atomizer for Solid Lubricants, Tool and
Workpiece Held on Force Dynamometer

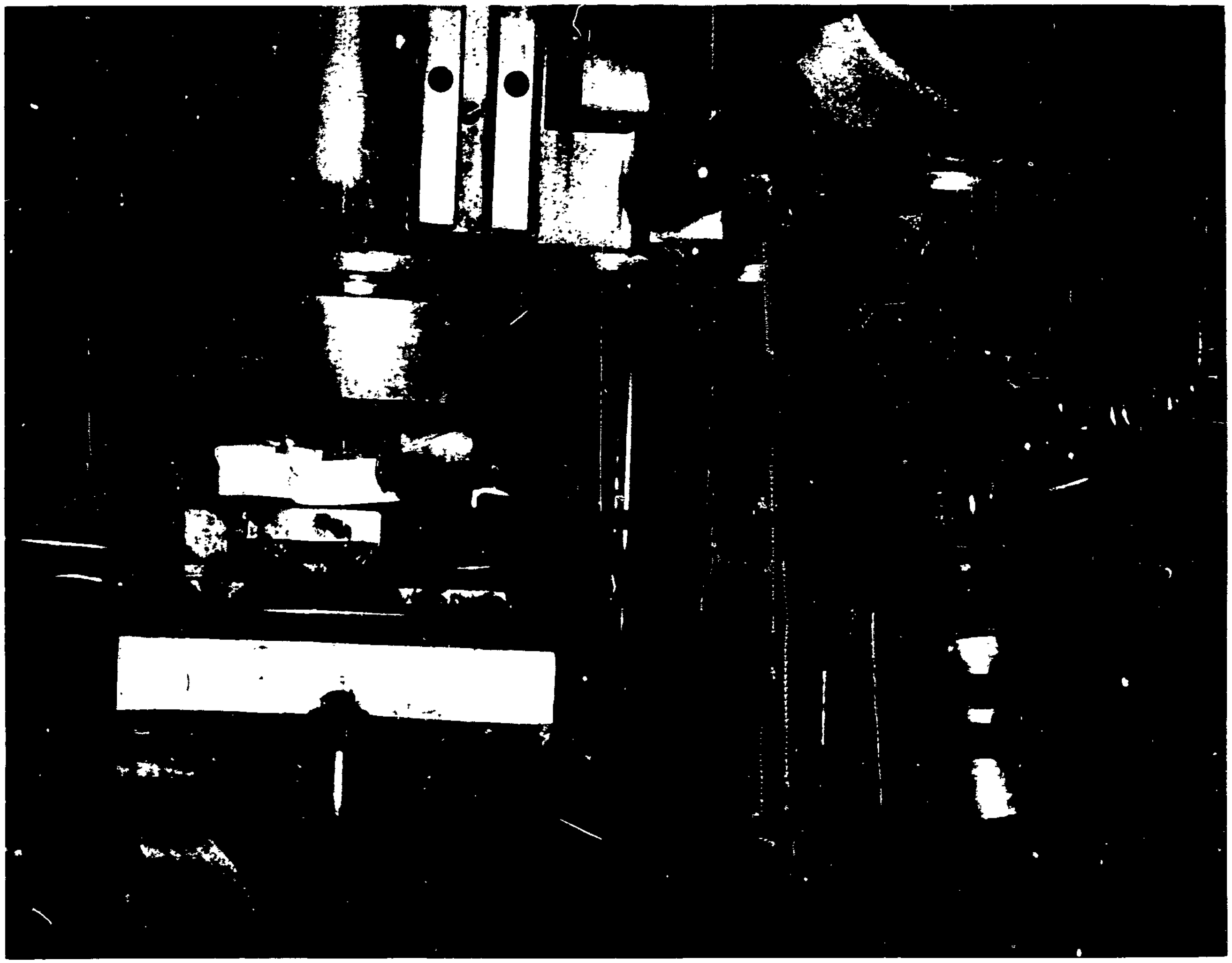
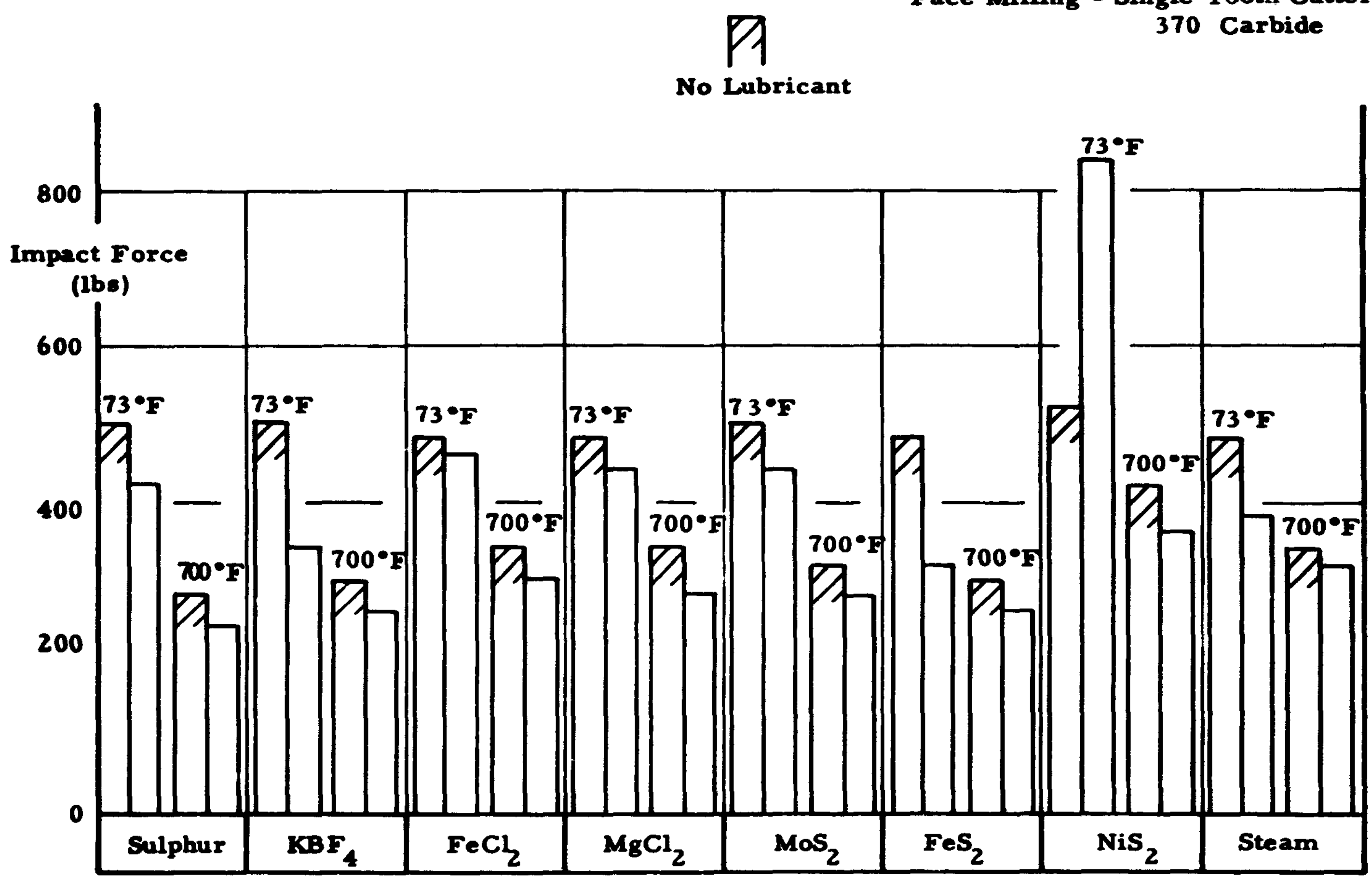


FIGURE 60

EFFECT OF SOLID LUBRICANTS ON MAXIMUM TOOL FORCE

FIGURE 61

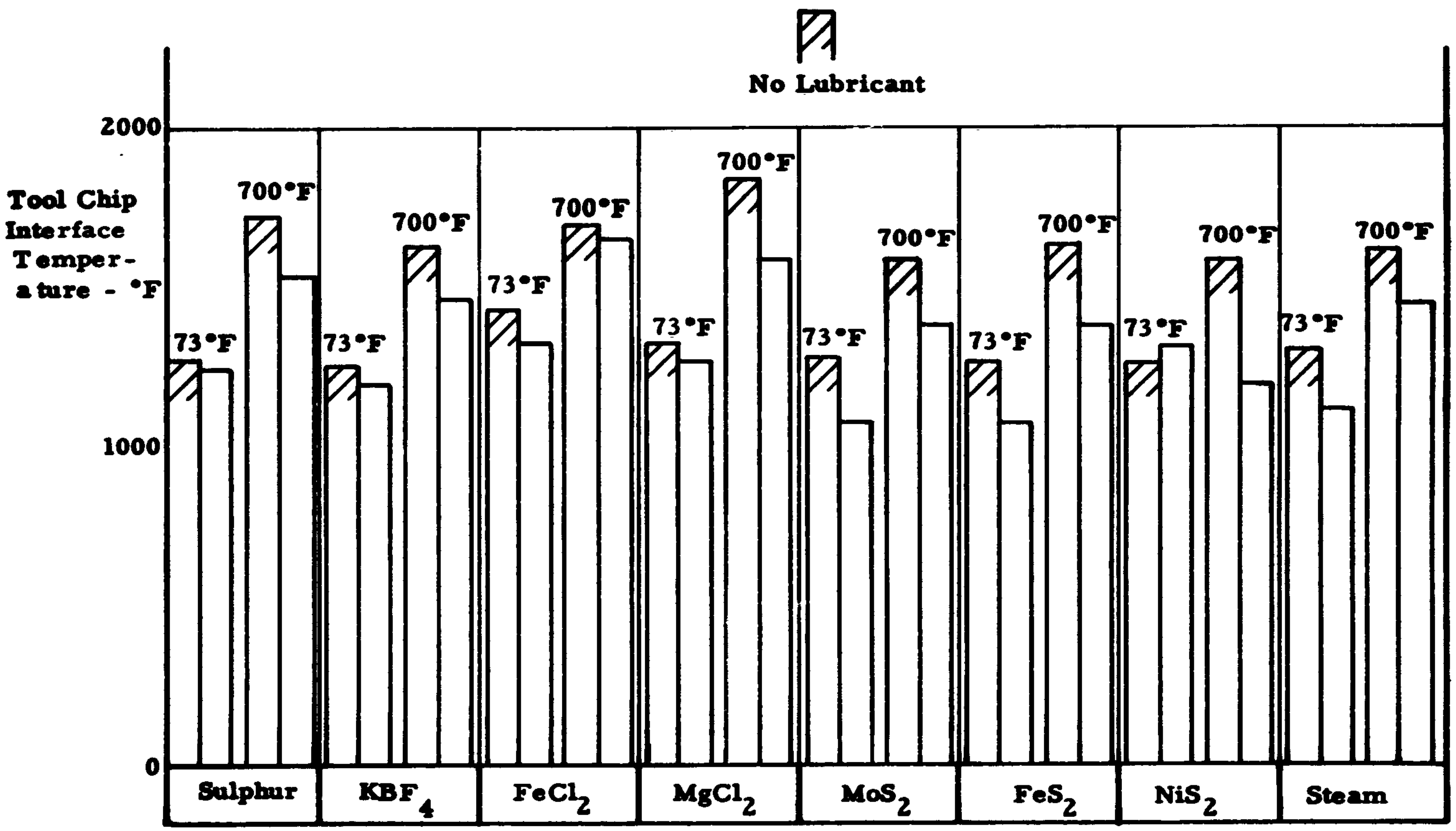
Cutting 460 BHN Thermold J
Equal Volumes of Metal Cut (1.1 cu. in.)
220 FPM .0135 IPR .0625 Depth
Face Milling - Single Tooth Cutter, 370 Carbide



EFFECT OF SOLID LUBRICANTS ON TOOL TEMPERATURE

Cutting 460 BHN Thermold J
Equal Volumes of Metal Cut (1.1 cu. in.)
220 FPM   .0135 IPR   .0625 Depth
Face Milling - Single Tooth Cutter, 370 Carbide

FIGURE 62



SUMMARY OF FORCE AND INTERFACE RESULTS WHEN USING VARIOUS LUBRICANTS

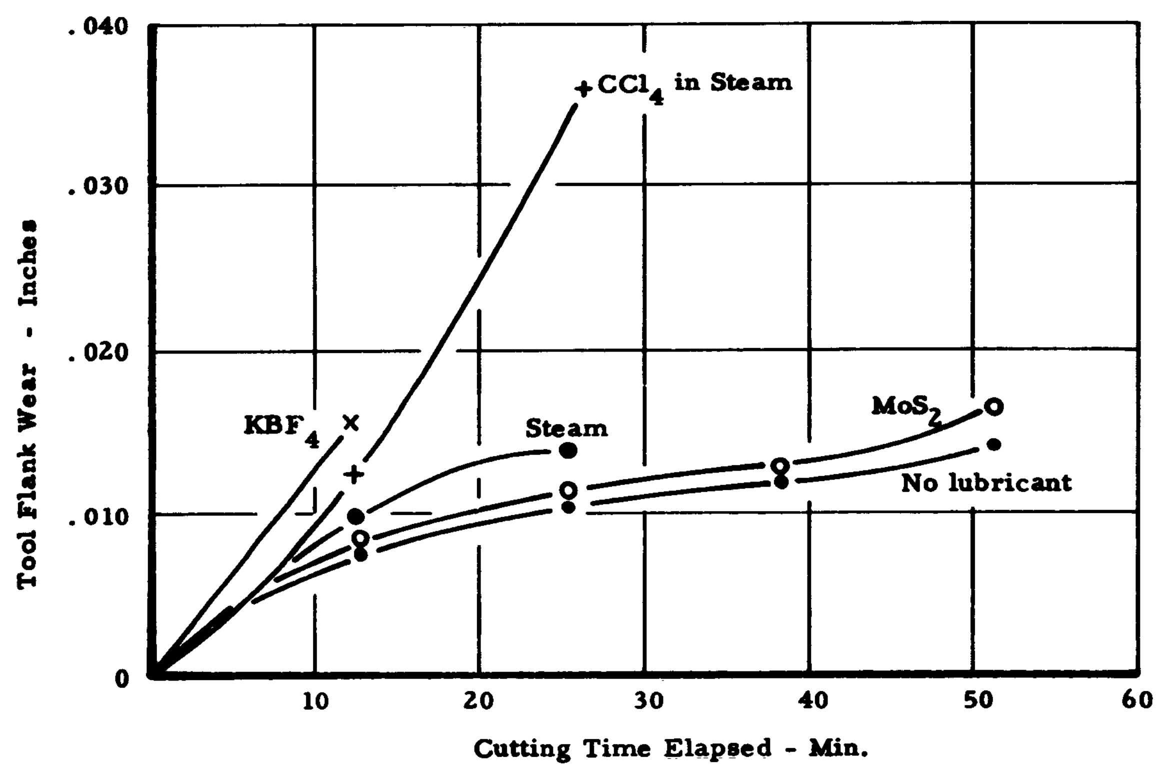
Material	Melting Point °F	Interface Temp. at Room Temp.	Reduction in Force	Reduction in Interface Temp.	Interface Temp. at Elev. Temp.	Reduction in Force	Reduction in Interface Temp.
Sulphur	-	1240	fair	poor	1530	poor	fair
KBF_4	986	1200	good	poor	1480	poor	fair
$FeCl_2$	1238	1420	poor	fair	1720	poor	poor
$MgCl_2$	1310	1280	poor	poor	1600	poor	good
MoS_2	2165	1090	fair	fair	1380	poor	fair
FeS_2	842	1200	good	fair	1380	poor	good
NiS_2	1472	1320	neg.	neg.	1200	poor	good

FIGURE 63

TOOL FLANK WEAR VS. TIME ELAPSED USING VARIOUS LUBRICANTS

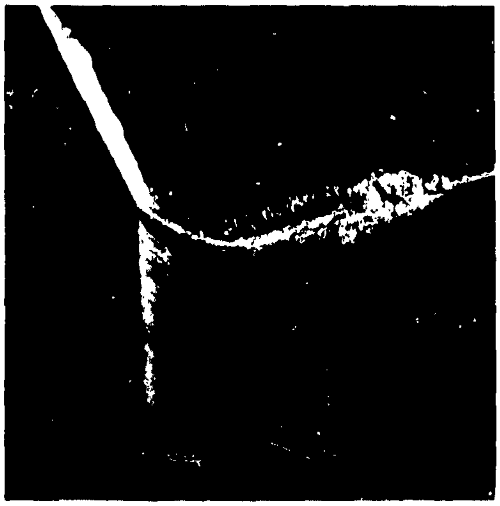
FIGURE 64

460 BHN Thermold J
370 Precision Carbide, 1/32 R
-5° Back Rake - 5° Side Rake
15° ECEA 15° SCEA
RPM 148 IPM 15/16
FPM 338 IPR .0064
1/16 Depth of Cut
Work Temperature - 700°F
Wear Land -.015



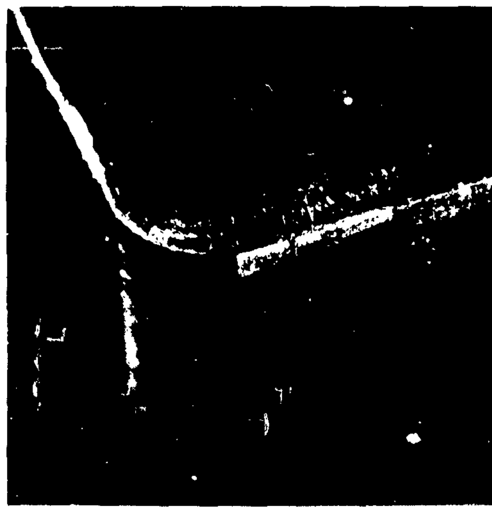
TOOL WEAR WHEN USING VARIOUS LUBRICANTS

.015 inch Flank Wear



KBF_4 - 12 min.

Steam - 31 min.



No Lubricant - 45 min.

CCl_4 (in steam) - 14 min.

MoS_2 - 45 min.

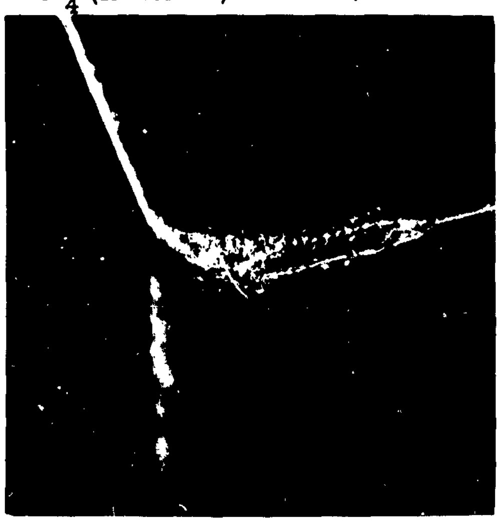


FIGURE 65

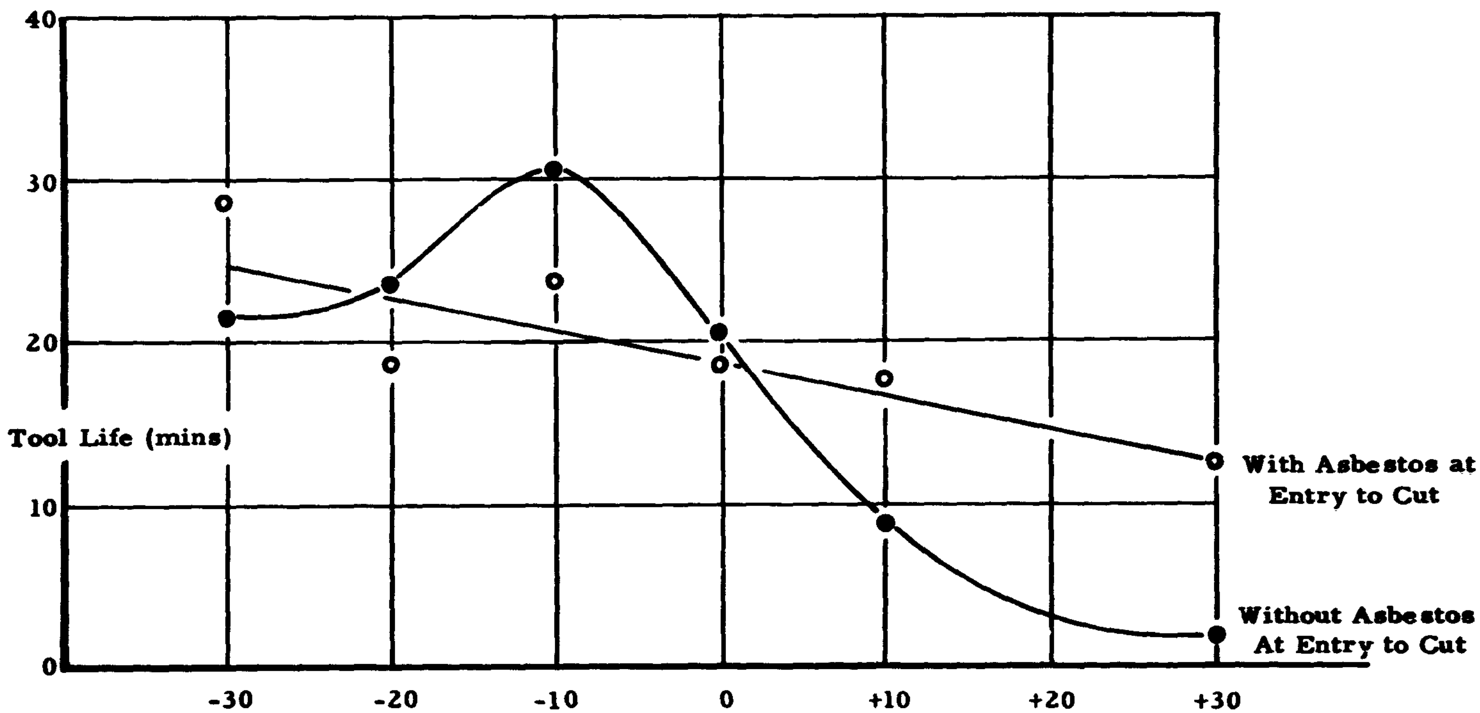
HOT MILLING APPARATUS

With Crysotile Asbestos at Entry

FIGURE 66

EFFECTS OF ENGAGEMENT ANGLE AND ASBESTOS AT ENTRY IN HOT MILLING

Work Material: 17-4 Mo, 360 BHN
Tool: 370 Carbide
Cutting Speed: 512 FPM, Feed: .0058 IPR
Work Temperature: 1000°F



Angle of Engagement

FIGURE 67

EFFECTS OF ENGAGEMENT ANGLE AND ASBESTOS AT ENTRY IN HOT MACHINING - FACE MILLING OPERATION

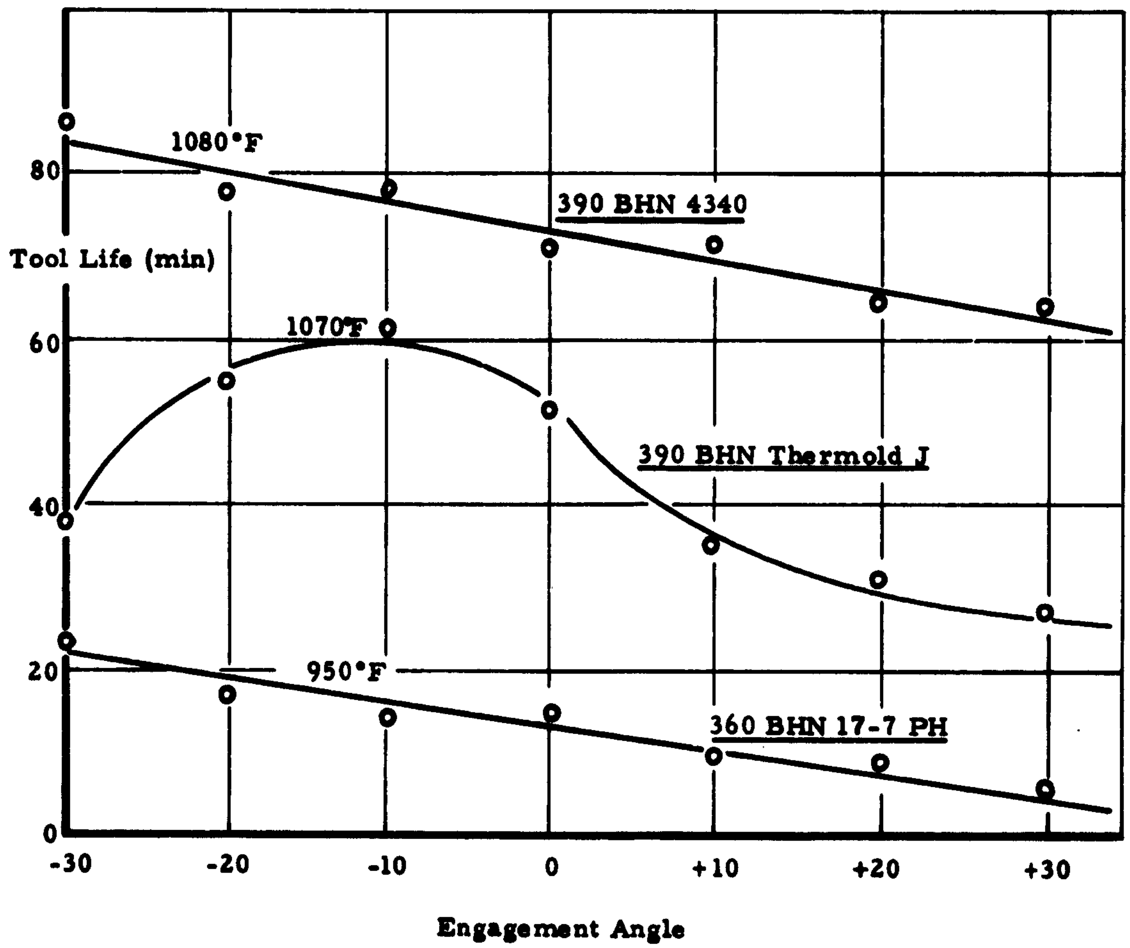


FIGURE 68

ACCELEROMETER MOUNTED ON CUTTING TOOL
Cutter Body, Tool Holder, Accelerometer,
Workpiece with Asbestos at Entry to Cut

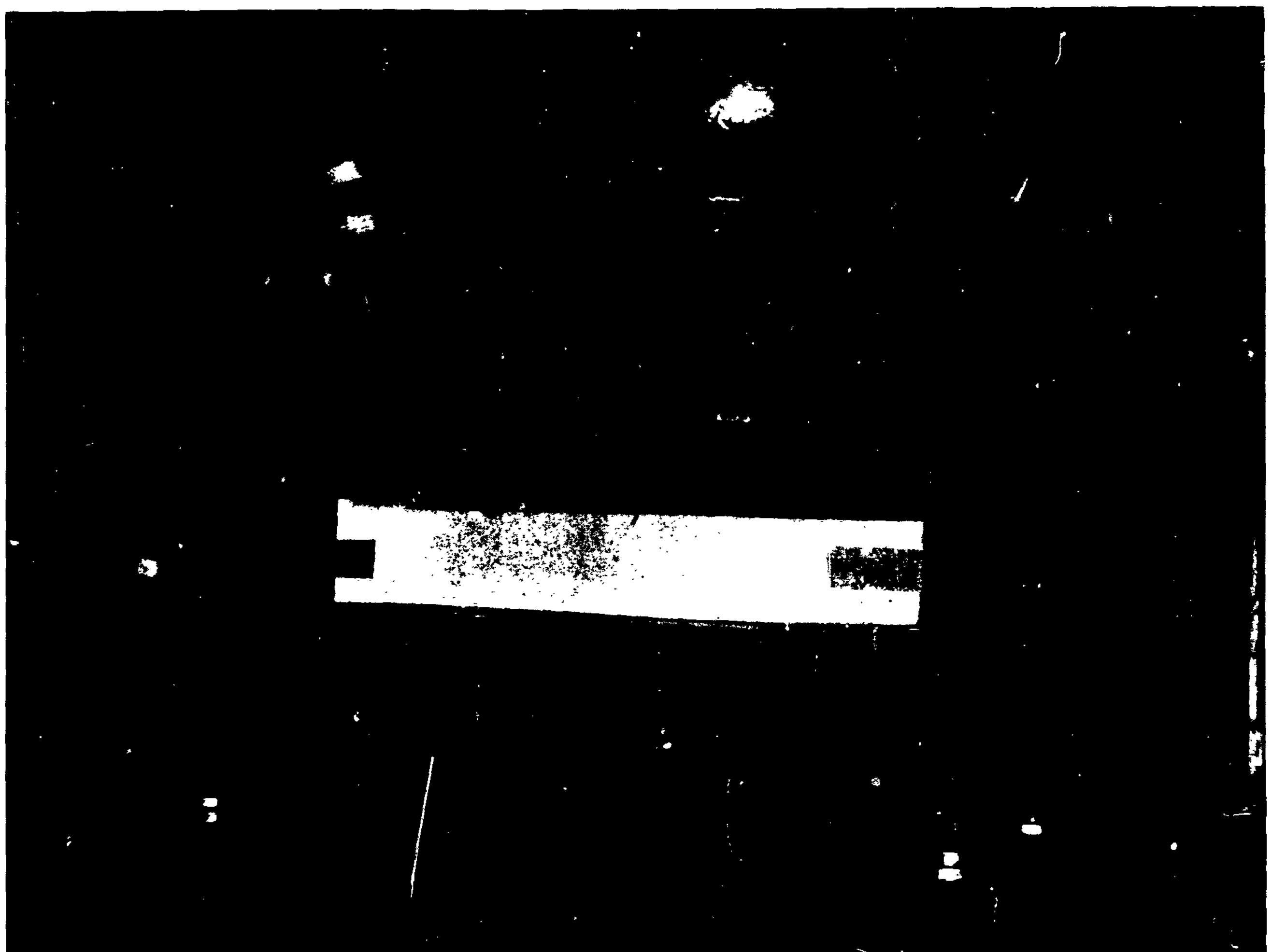


FIGURE 69

IMPACT FORCE MEASURING APPARATUS
Accelerometer, Mercury Pot, Cathode Follower and Oscilloscope

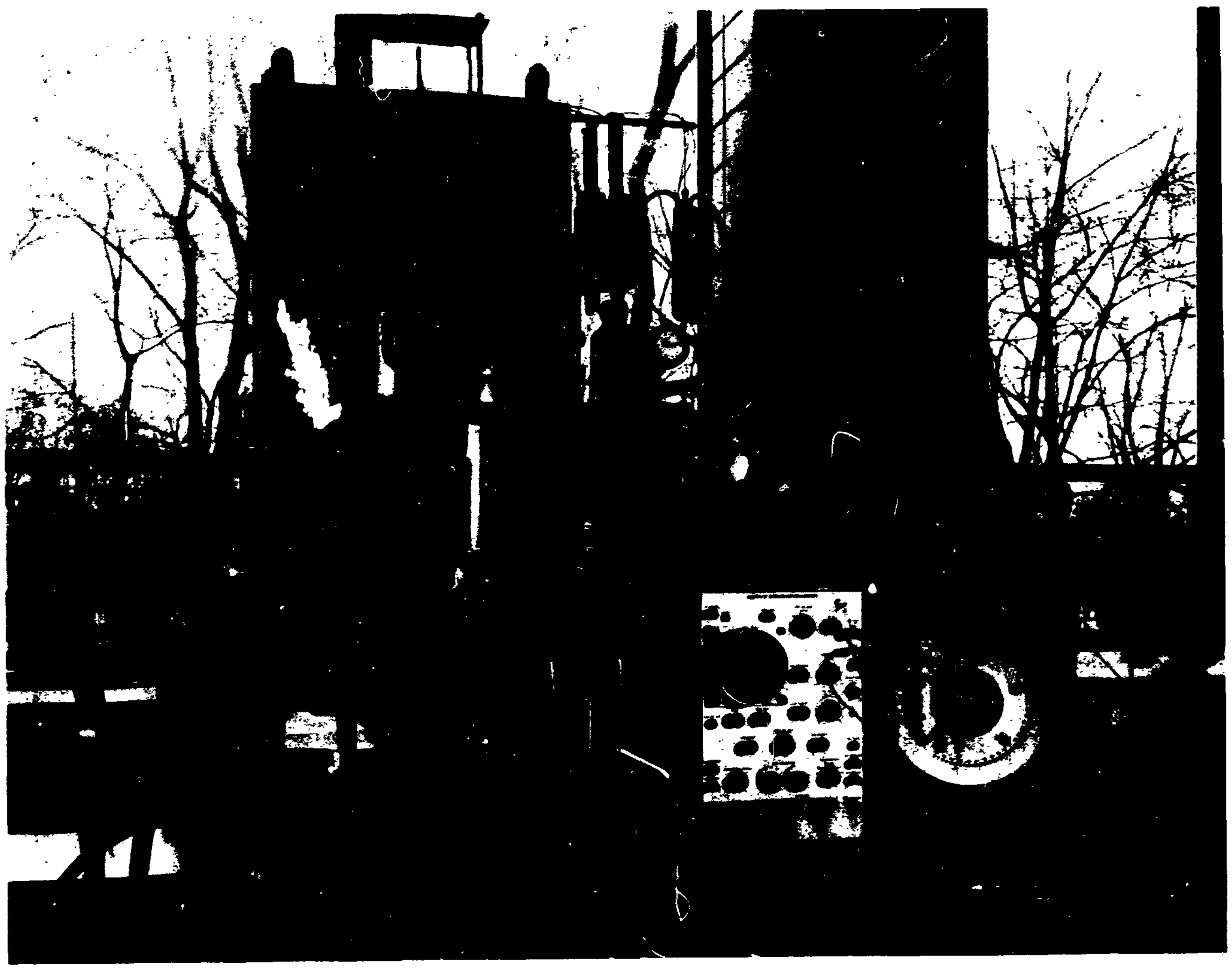
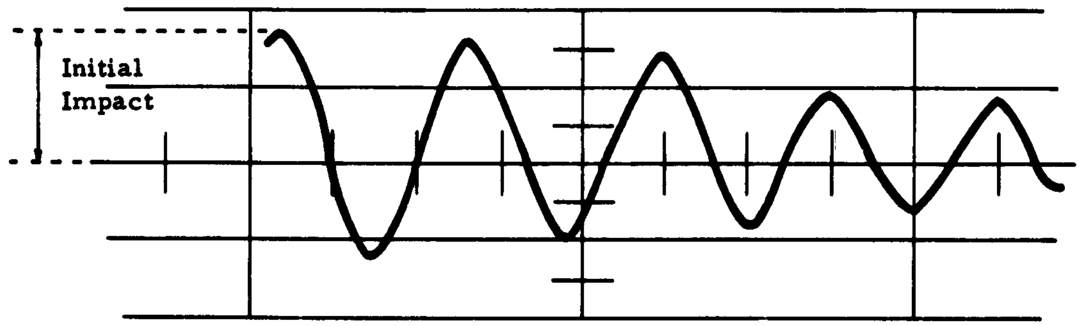
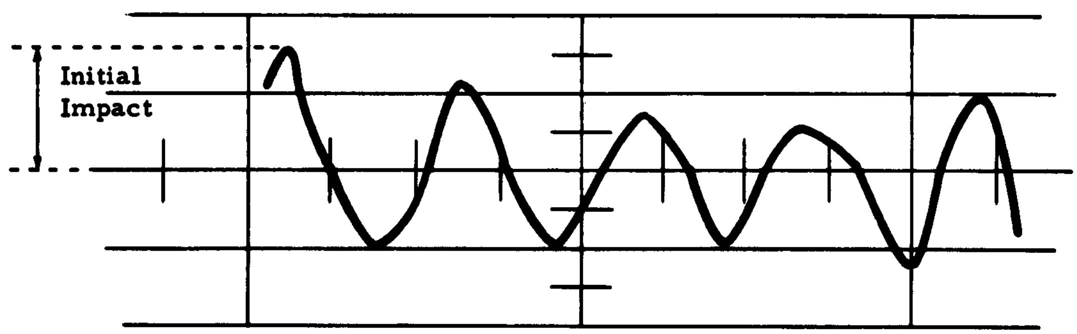


FIGURE 70

TYPICAL OSCILLOSCOPE TRACE OF IMPACT FORCES MILLING HAYNES ALLOY NO. 25 WITH AND WITHOUT ASBESTOS AT ENTRY TO THE CUT



Without Asbestos



With Asbestos

FIGURE 71

EFFECT OF SILICONS ON FACE MILLING HAYNES ALLOY NO. 25

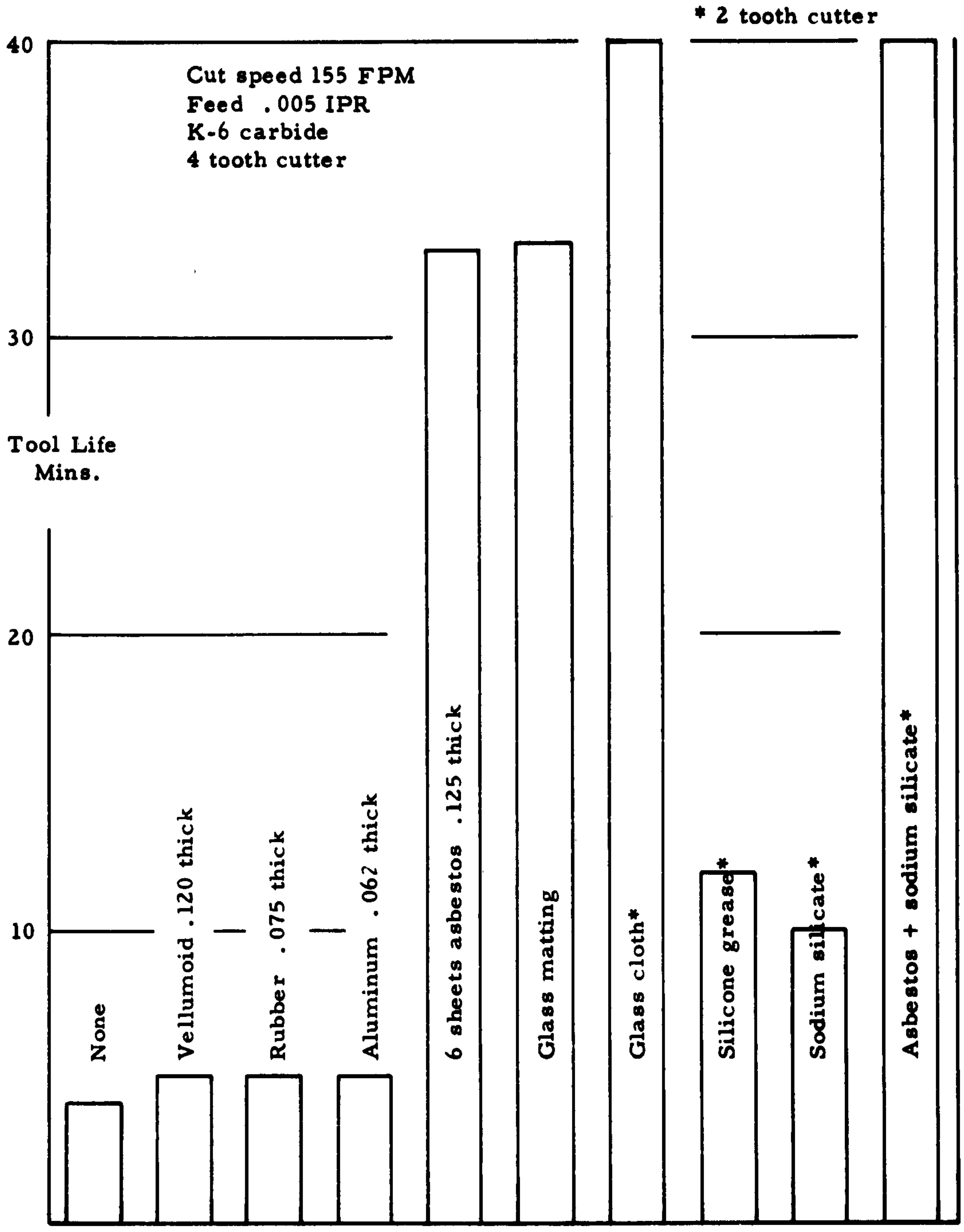


FIGURE 72

PERIPHERAL MILLING TESTS

Objective

Obtain sufficient peripheral milling data on PH 15-7 MO stainless steel to provide the basis for a valid economic comparison on the methods of manufacturing a "T" section extrusion described in the economic section.

Apparatus

The workpiece was machined on a No. 3 Cincinnati horizontal dial type milling machine. The 30 KW Inductron power supply used for other tests was used to provide the R. F. resistance heating power for these tests. A thermodot radiation pyrometer was used to determine the required induction settings to achieve the proper workpiece temperature during these tests. It was not used during the production tests, however, since proper operating conditions had already been established. Under shop conditions a radiation pyrometer would be used during set-up to determine the power supply settings required to achieve the desired temperature.

The cutter was an arbor mounted side mill with grade 78B brazed inserts. Cutter geometry and additional data are given on Figure 73.

Results

To select the workpiece temperature for use in the comparison, tool life tests were conducted at various workpiece temperatures from room temperature to 900°F. Results of these tests are shown in Figure 73. It can be seen that the greater part of the tool life improvement is obtained at temperatures below 500°F. Above this temperature tool life continues to increase, more slowly, until a maximum is reached around 800°F. The low temperature for maximum tool life is probably due to the gumminess of the solution treated material. This behavior is the reason it is preferable to machine the precipitation hardening steels in the aged condition, either at room or elevated temperature. Unfortunately, this part could not be machined in the aged condition, because of the requirements of subsequent operations. Since increase in the workpiece temperature increases the distortion and the chance of metallurgical damage, it was decided to limit the workpiece temperature to 500°F.

In industry the extrusion is presently being machined at 60-80 fpm with high speed steel tools. This cutting speed yields a tool life of 100 linear feet of extrusion, which is the normal lot size machined. To assist in making a direct comparison we also chose cutting conditions to give tool life of 100 linear feet. Tool life tests were conducted at various speeds at room temperature and at 500°F. These results, shown in Figure 74, were extrapolated to determine that the room temperature tests should be run at 140 fpm and the 500°F tests at 260 fpm. The feedrate of .0055 inches per tooth was chosen to provide a good surface finish and still get under the work hardened layer developed when machining this material.

TOOL LIFE VS. WORKPIECE TEMPERATURE ON PH 15-7 MO 176 BHN

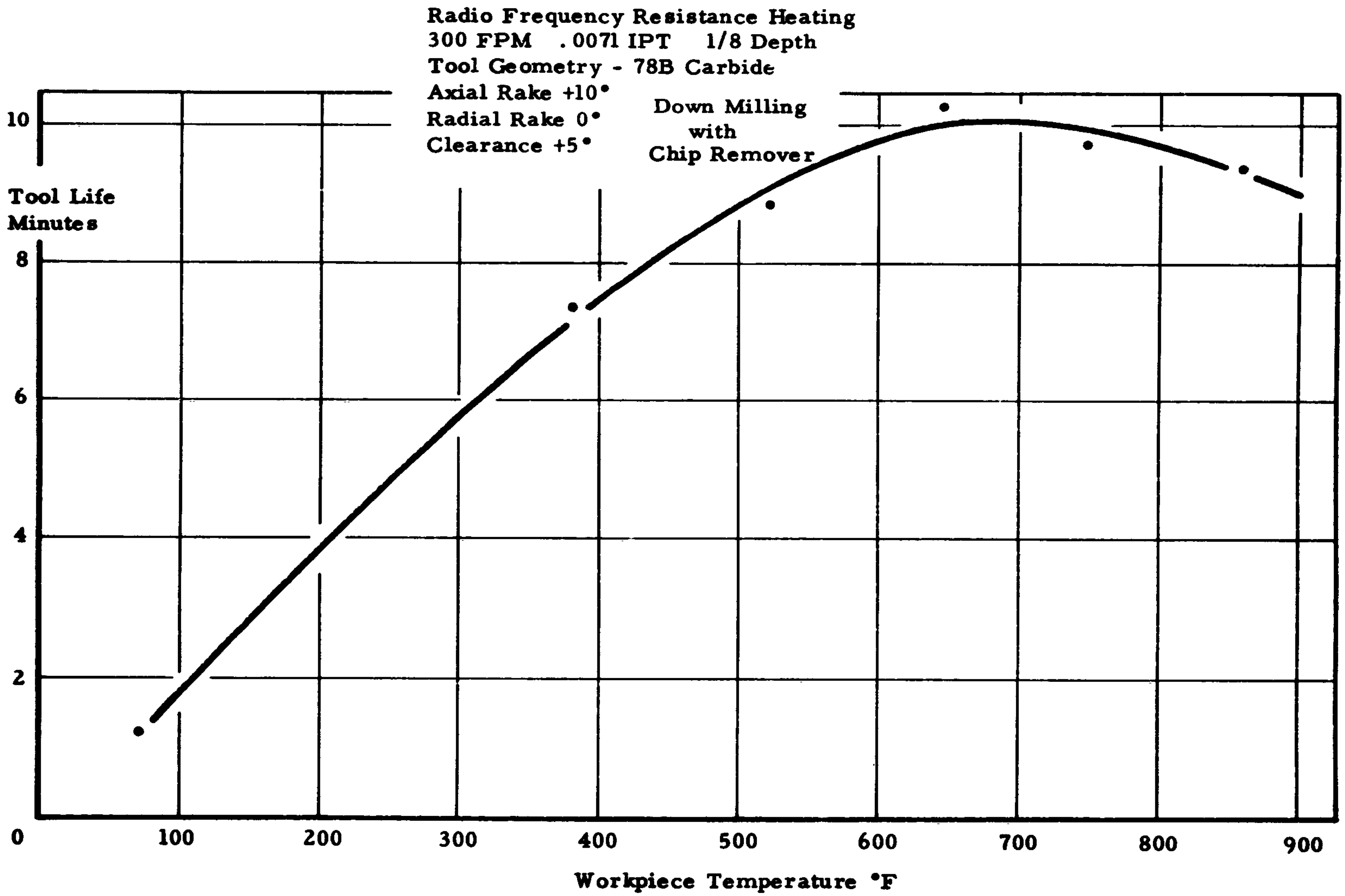


FIGURE 73

TOOL LIFE VS. CUTTING SPEED MILLING PH 15-7 MO AT ROOM AND ELEVATED TEMPERATURE

Feed .007 IPT — 1/8 Depth — 176 BHN

Tool Geometry
- Axial Rake +10° — 78B Carbide Single Tooth Cutter
- Radial Rake 0° — Down Milling with Chip Remover
- Clearance 5° — .030 Flank Wear - Tool Life Criterion

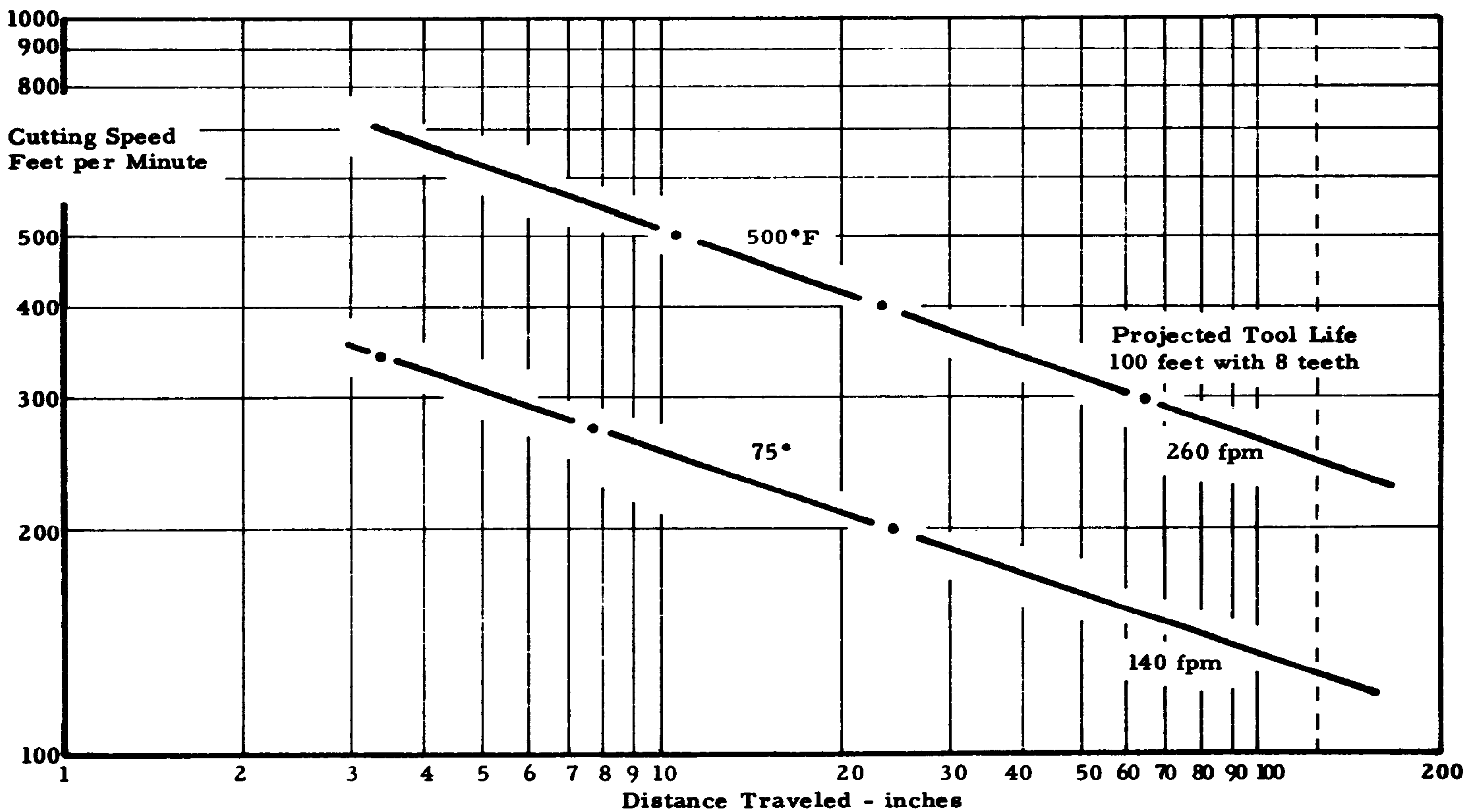


FIGURE 74

END MILLING TESTS

Objective

Develop workable techniques for hot end milling and evaluate the effect of workpiece temperature on the end milling machinability of Thermold J.

Apparatus

The end milling evaluations were conducted on the No. 3 vertical dual power to insure a rigid set-up. Heating power was supplied from the 30 KW, 1.2 megacycle "Inductron" to a special radio-frequency resistance heating apparatus as shown in Figure 75. The apparatus and its development is described in detail in the section "Heating Studies". The carbide end mills used in this test were grade K6 and 1/2 inch diameter, four flutes, 14° helix angle, 5° clearance angle, and a 45° x 1/16 inch chamfer. Four flute HSS end mills with 25° helix, 5° clearance and 45° x 1/16 chamfer were also used.

The test cuts consisted of milling a through slot 1/2 inch wide by 1/4 inch deep in a 12 inch x 1 inch test piece of 480 BHN Thermold J. After each pass the block was milled flat so that all passes were made under identical conditions. Also after each hot machining pass the block was checked to insure that no tempering had taken place which would change its hardness and consequently the machining conditions.

Results

The results of the end milling tests are shown in Figure 76. It may be seen that rapid failure occurred at room temperature with carbide cutters, but 20 inches of work were cut at 575°F and 45 inches at 980°F, an increase of thirteen and thirty-fold respectively from the best room temperature test. When compared with H.S.S. at room temperature (a common machining practice with this material), for a tool life equivalent to 30 inches of cutting, the cutting speed can be increased from 30 fpm with HSS to 180 fpm with carbide at 980°F -- a six-fold increase in metal removal rate.

Discussion

When machining with carbide end mills at room temperature no success was apparent. Tool life ranged from 1.0 inches to 1.5 inches cut with speeds of 55 to 210 fpm and a feed of .002 ipt. Tool failure in all cases was due to chipping and breakage. At elevated workpiece temperatures, data were obtained in the "knee" of the tool life curve where the linear Taylor relationship no longer holds. While we would have liked to obtain information at higher speeds to give a better picture of the tool life relationship we were limited by the available spindle rpm. This limitation is unfortunately common on all standard milling machines with sufficient rigidity for this type of work, and the limitation is only raised slightly by high speed machines.

When cutting with any tool material, the tool life increases with decreasing speed as given in the Taylor equation, $VT^n = C$ (cutting speed times tool life raised to the power "n" equals a constant), only within certain limits. As the cutting speed is decreased a point is reached where the character of the wear changes and the slope of the curve changes drastically. The wear is no longer due to the abrasion of minute particles from the tool face, but the chipping out and ploughing of tool material. This causes erratic and rapid failure of the cutting edge. This phenomenon is common to all tool materials, but is most evident in the harder and more brittle ones. The speed at which it occurs is determined by the tool material, tool geometry, and feed rate.

It must be noted that hot end milling of Thermold J with HSS mills was not successful. It appears that the decrease in tool life at an elevated temperature resulted from two causes:

(1) the strength-temperature properties of the tool material

(2) the burying nature of the end milling process.

The temperature-strength curve for Thermold J shows a small decrease in strength up to 400°F and, while this loss of strength may be sufficient to increase tool life when performing an operation where the cutter is cooled by being away from the hot workpiece throughout a large fraction of each revolution with a relatively temperature insensitive tool (such as face milling, see Figure 40), it is insufficient to counteract the increase in tool temperature when the H.S.S. tool is not cooled. In end milling operations, such as slotting, the cutter tooth is in contact with hot material and hot air convected from the workpiece the entire time it is in the cut. When the first tooth contacts the hot workpiece, it is at ambient (room) temperature and when it emerges from the cut it is at some interface temperature. As it continues around it cools, slowly however, since it is bathed in hot air and heat is being conducted from the tooth now in the cut. It enters the cut the second time at some temperature above ambient and leaves at a higher interface temperature. This build up of heat continues until an equilibrium is reached where the heat added in the cut is removed by conduction through the end mill to the machine and by convection. At equilibrium, the temperature at entry to the cut is considerably above ambient and approaching the temperature of the work-piece, and the interface temperature is higher. Unless this loss in tool life due to the higher interface temperature is compensated for (in case of the HSS cutter it was not) by a reduction in strength a shorter tool life will result.

R. F. RESISTANCE HEATING FOR END MILLING

Electrodes and Special Replaceable Return Conductor

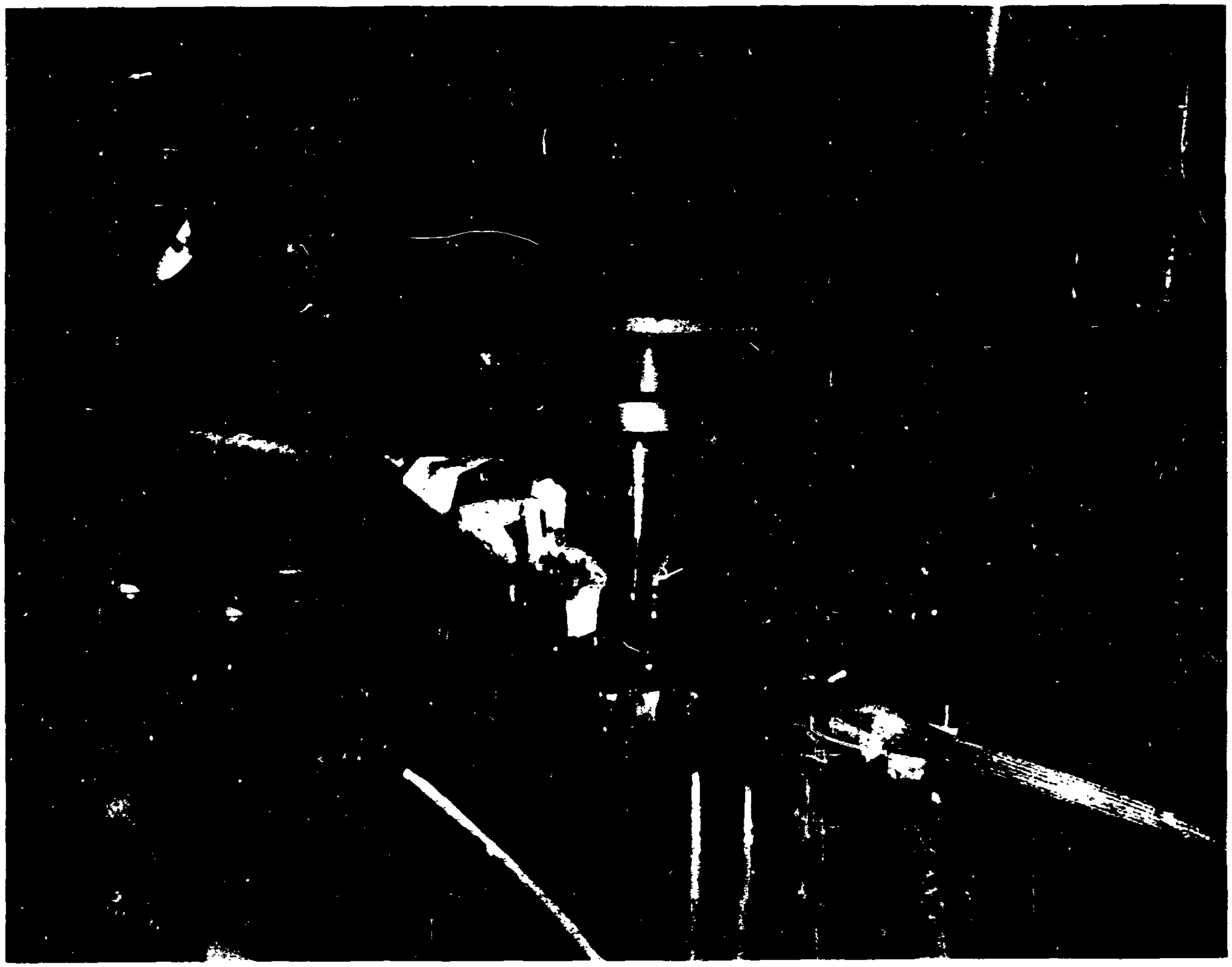


FIGURE 75

CUTTING SPEED VS. TOOL LIFE AT VARIOUS WORKPIECE TEMPERATURES - END MILLING THERMOLD J - 480 BHN

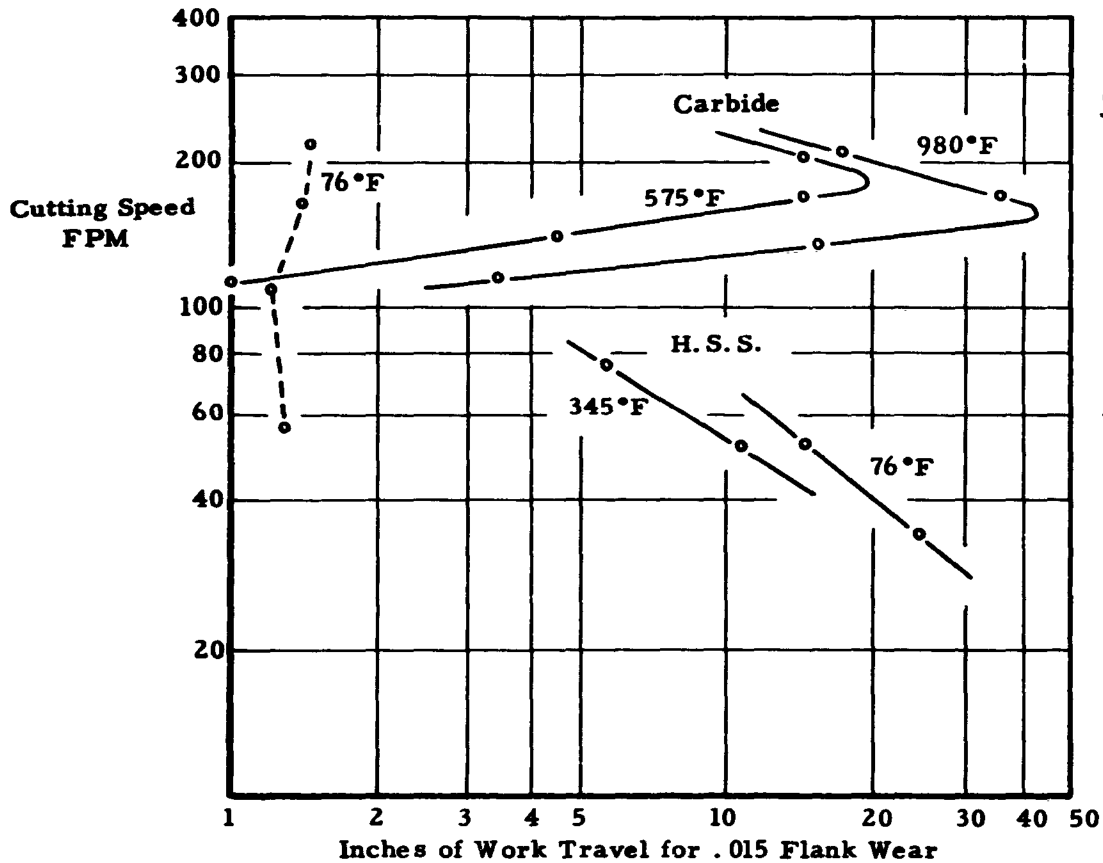


FIGURE 76

Carbide Tool: K6 1/2 dia.
4 flute end mill
Helix Angle: 10°
Corner Angle: 1/16 x 45°
Side Clearance: 5° pr, 10° sec
End Clearance: 5° pr, 20° sec
Feed: .002 IPT

High Speed Steel Tool: 1/2 dia.
4 flute end mill
Helix Angle: 25° mill
Corner Angle: 1/16 x 45°
Side Clearance: 5° pr, 10° sec
End Clearance: 5° pr, 20° sec
Feed: .002 IPT

DRILLING TESTS

Objective

Determine the feasibility of hot drilling, determine the effect of drilling temperature on various drill materials, and establish drill life-cutting speed curves for various workpiece temperatures.

Apparatus

The tests on AISI 4340 steel with high speed steel and cobalt high speed steel drills were conducted on a 21" drill press. Through heating of the workpiece was provided by a thermostatically controlled 3000 watt electric furnace. The apparatus is shown in Figure 77.

Since the drill press used for these tests had a limited feed range, the tests with carbide tipped die drills and solid carbide drills were conducted on a Number 4 vertical milling machine. A drilling dynamometer was installed to measure the torque and thrust force. The set-up is shown in Figure 78.

Increase in thrust force was the criterion used to determine tool life, i.e., the drill was considered to have failed when the thrust force increased sharply. This criterion considers a drill to have failed when a piece is chipped out or excessive wear occurs. When carbide drills are used, chipping and excessive wear must be avoided because of high grinding costs.

Results

H.S.S. drills: H.S.S. drills of 1/4 inch diameter were tested on a block of AISI 4340 steel (534 BHN or 54 Rc) at room temperature with minuscule tool life at 25 fpm. When a feed of 0.005 inch per revolution was used (the smallest feed available on the machine), drill failure was by fracture. Hand feed usually gave wear failures. A very slight improvement in drill life was obtained when the block was heated to 300°F but the tool life dropped off sharply above this temperature. It was felt that hot drilling would have a better opportunity of success with less heat-sensitive tool materials.

Cobalt H.S.S. Drills: Cobalt H.S.S. drills of 1/4 inch diameter gave an increase in drill life both at room temperature and at 300°F but the improvement was not great enough to warrant further study at this time.

Carbide Tipped Drills: Carbide tipped drills of 9/16 inch diameter gave greatly improved tool life for holes shorter in depth than the length of carbide tip. When deeper holes were drilled, the drill shank was fractured at the base of the carbide insert due to restrictions in chip flow inherent in this type of drill. While these drills might be satisfactory for shallow holes, it was felt that the studies should be concentrated on deeper hole drilling.

Solid Carbide Drills: When solid carbide drills of 1/2 inch diameter were used with conventional geometry at elevated temperatures, binding and pickup on the margins was experienced. To combat these shortcomings, two modifications were carried out: (1) the margin was ground with a 5° clearance (in place of the circle grind) for 1/4 inch from the end of the cutting lip; (2) a back taper of 0.002 inches per inch was ground from the end of the clearance face up the rest of the drill. These modifications prevented the surface of the block from shrinking onto the drill when it cooled and provided a cutting edge to cut the slightly smaller surface hole when the drill was retracted. Since most of the failures were due to chipping of the primary cutting edges, a primary 0° axial rake face was ground on the cutting edge in place of the normally positive axial rake. This combined with the actual negative radial rake gives a negative normal rake and less chipping. A spiral point grind was used in the tool life tests.

Tool Life

The tool life-cutting speed curves at various temperatures for 1/2 inch C-2 grade solid carbide drills cutting AISI 4340 steel (509 BHN, 52 Rc) are shown in Figure 79. The room temperature tests show the highest tool life while the 400° test gives the lowest. This appears to be due to the fact that 4340 loses strength slowly with increasing temperature at lower temperatures. Thus, the bulk of the drill is heated by heat transfer from the block resulting in higher tool chip interface temperatures without much loss in strength of the material cut. Since the rate of decreasing strength with temperature increases at higher temperatures, the 700°F and 1000°F tests give better tool life. It is possible that at 1200°F, the tool life might be better than at room temperature; however, tempering of the workpiece was already severe at 1000°F (a loss of 12 points Rc) and it was felt that going to higher temperatures would be fruitless with through heating methods.

Modified carbide drills (with 5° clearance ground on the margin and .002" per inch back taper and a 0° axial rake) were tried on 437 BHN 17-4 MO stainless steel. Drill failure was by fracture at both room temperature and 700°F. The holes were sectioned to determine the cause of the failure. It appears that packing and welding of the chips on the flutes caused the failures. It would appear that hot drilling of fairly deep holes at the fine feeds which must be used on these workpieces, unfortunately provides time for the cutting end of the drill to reach high temperatures. Apart from the tendency of the thermally expanded drill to bind on the periphery, conditions then exist which encourage welding and seizure of the chips on the flutes to the inside diameter hole, resulting in catastrophic drill failure. Life curves obtained, drilling 440 BHN 17-4 MO with high speed steel drills at various speeds and temperatures, are shown in Figure 80. It appears that the optimum workpiece temperature is approximately 300°F to 350°F for HSS drilling of this material. Cutting at 29 fpm, approximately three times as many holes were obtained at 300° as were obtained at room temperature before non-catastrophic drill failure. Less improvement can be realized at higher speeds. The probable explanation of the optimum value of workpiece temperature from maximum drill life is that although the strength of 17-4 MO stainless steel does not appreciably diminish in the increase of temperature to around 350°F, the work hardening capabilities of the material are greatly reduced. This lessened work hardening of the material on the transient surface being cut, means that the cutting edges of the drill are subjected to less abrasive wear. The benefits accruing from this, however, are being continually offset by the drill temperature increasing, such that above 350°F workpiece temperature, the hot hardness of the drill has been reduced to the level adversely affecting drill wear rate.

Drilling U.S. Steel X-200

In a tool research report from Goodyear Aircraft Corp. entitled "Machining Thermal Resistant Materials at Elevated Temperatures"[46], Mr. R.J. Moldovan reports on the drilling of U.S. steel X-200 air steel (53 to 56 Rc) at room temperature and elevated temperatures when drilling through 3/8" X-200 into an aluminum backup plate, the cutting conditions were as follows: 1/4" diameter solid carbide twist drills with point angles of 118° and 125°, relief angles, 5° and 7°, flute length 2°, cutting speed, 65 fpm, feed .0005 ipr, water soluble oil, cutting at room temperature. These tests showed approximately 30 holes were drilled at room temperature, 100 holes at 600°F. A smaller number of holes could be drilled at 500° and a larger number could be expected by increasing the feed to .001 ipr at 600°F. The workpiece was through heated with an automatically controlled resistance heating unit.

HOT DRILLING APPARATUS

Drill Press, Workpiece, and Electric Furnace

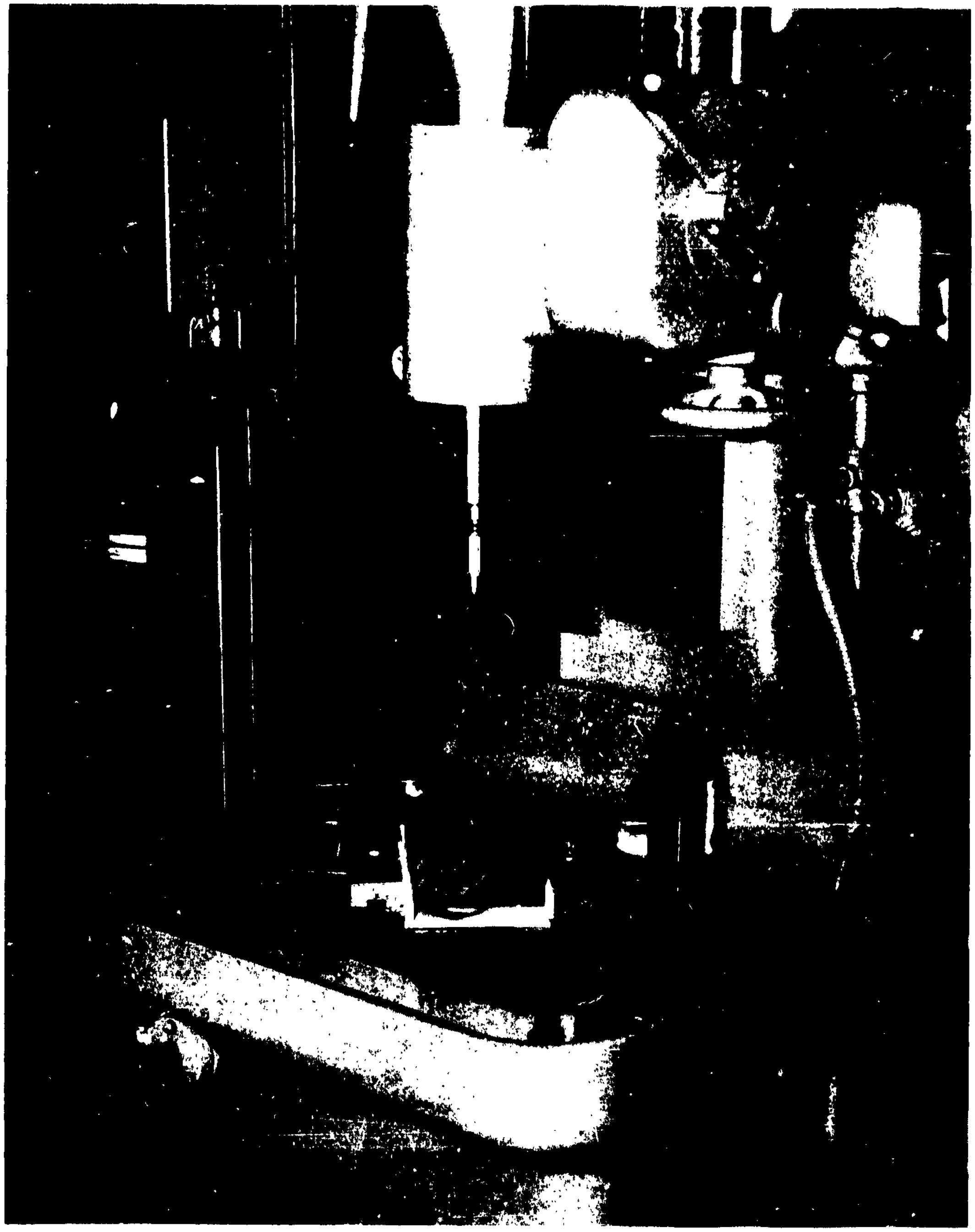


FIGURE 77

HOT DRILLING APPARATUS
Milling Machine Used as Drill Press, Drilling Force
Dynamometer, and Amplifier-Recorder

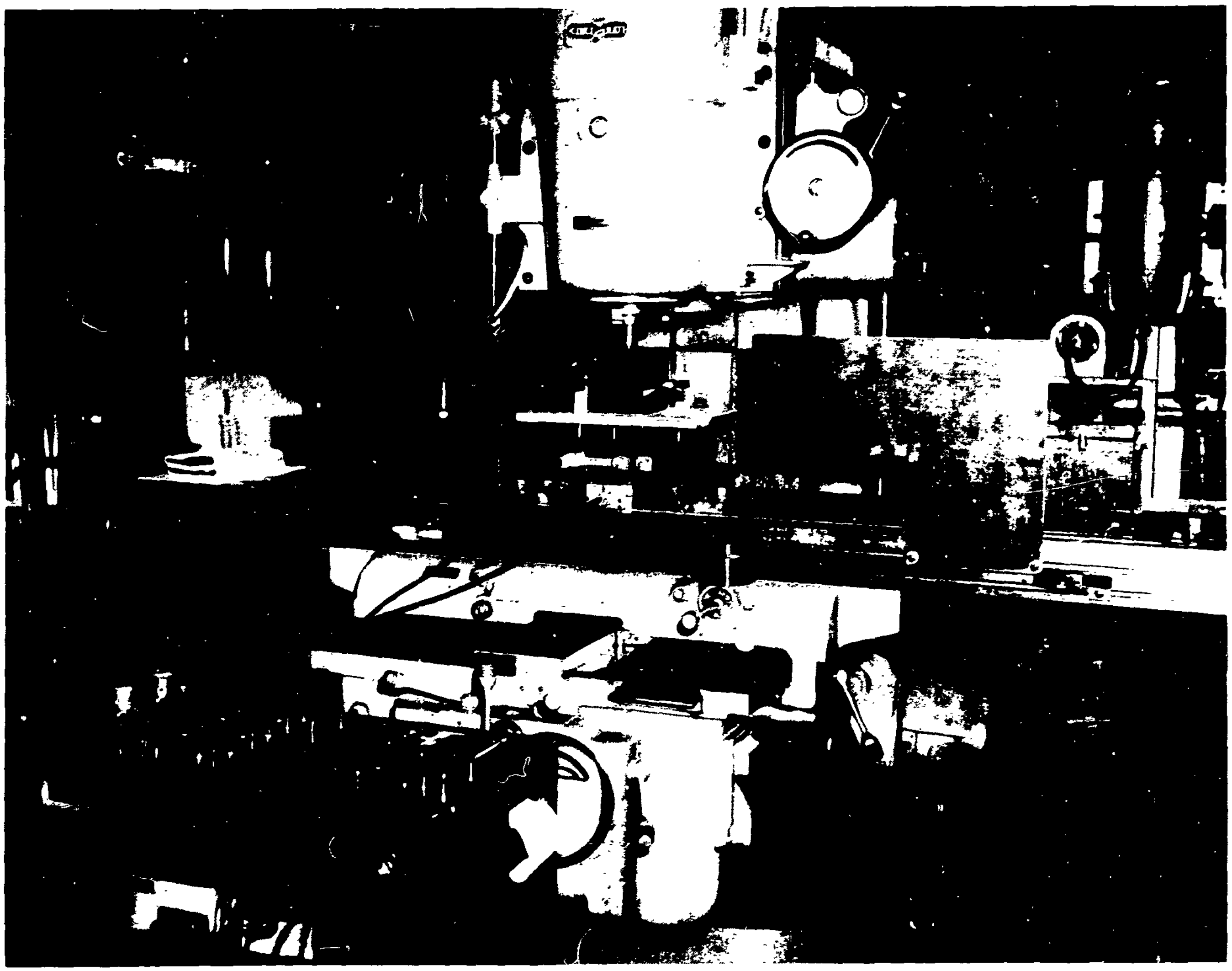


FIGURE 7ʋ

EFFECT OF TEMPERATURE ON TOOL LIFE CUTTING SPEED RELATIONSHIP

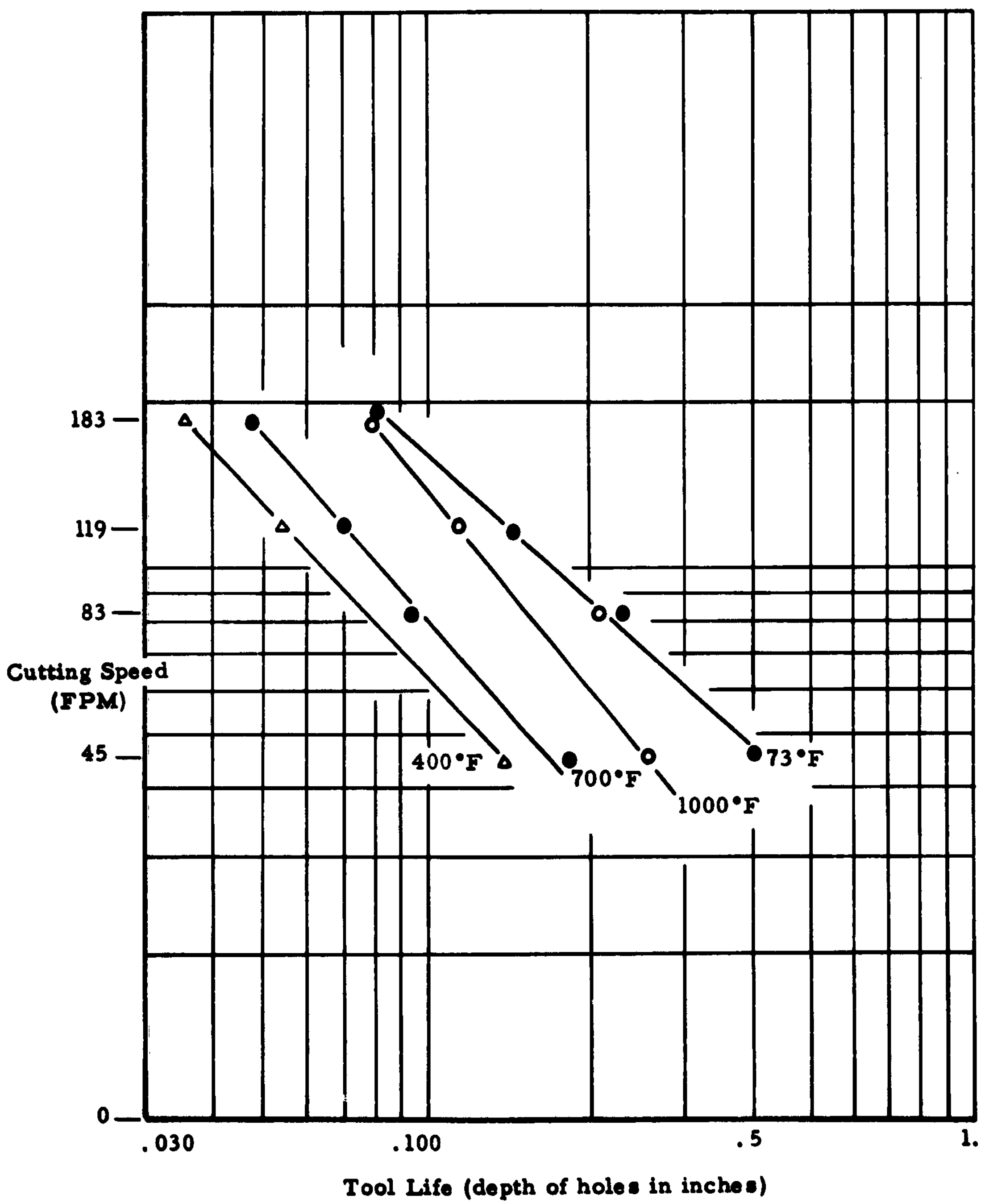
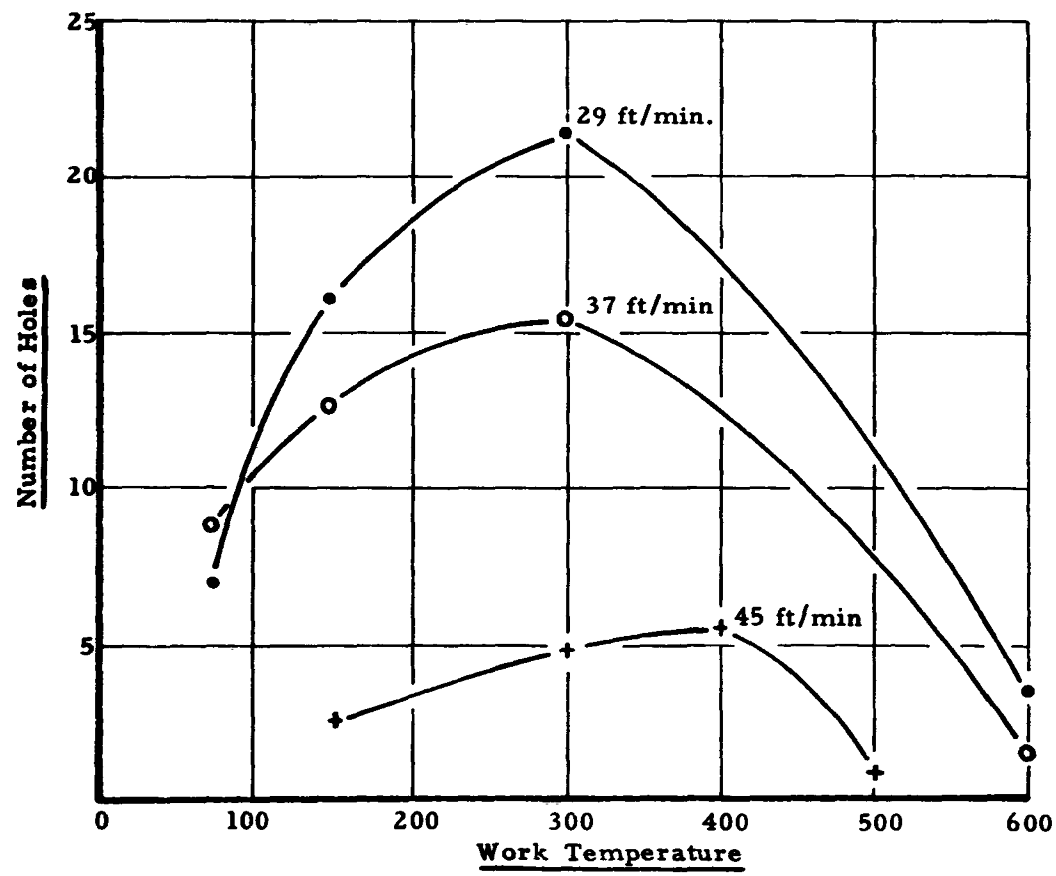


FIGURE 79

TOOL LIFE VS. TEMPERATURE AT VARIOUS CUTTING SPEEDS IN DRILLING



Drill: H. S. S.
Diameter: 1/2, length 2-3/4
Point Angle: 118° Helix Angle 29°
Point Grind: Spiral Point, Clear: 7°
Depth of Hole: 1" blind hole
Drilling: AM 350, 437 BHN
End Point: Increase in Thrust Force

FIGURE 80

HEATING STUDIES

Objectives

Develop effective heating methods which localize the heat in the zone of cutting, since the presently available heating methods are not effective on all materials, and for the material on which they are effective do not concentrate the heat exclusively in the shear zone, but heat other areas of the workpiece with consequent thermal damage, distortion, and lower efficiency.

Ideal Heating

In order to evaluate various heating methods, the characteristics of an ideal method must first be determined to provide a basis for comparison. The ideal heating method heats only the shear zone, since the plastic deformation of chip formation occurs in this zone. If any other area is heated, this heat is lost contributing to inefficiency. The method should not allow the area beneath the shear zone (the material beneath the depth of cut) to be heated. If this occurs, there is a possibility of heat damage to the material left behind. The ideal heat source must quickly raise the temperature so that it can keep ahead of the cutting tool. This requires a high specific heat input (B.T.U./sec/in^3). The method should be easy to control and provide a wide range of constant temperatures. Its results should be reproducible. It should be easy to set up and should not be dangerous to the operator.

Flame Heating

Flame heating has been used in hot machining with varying results since its inception. Flame heating in its simplest form is a welding torch played on the workpiece ahead of the cutting tool. The technique may be refined by using a multi-flamed heating head to increase the BTU output and concentrate the heat. Acetylene, propane and natural gas are generally used with oxygen as fuels. Figure 81 shows the flame heating set-up used for the orthogonal turning tests. Propane gas and oxygen were used with the multi-tipped water cooled burner to heat the workpiece. Pressure valves and a rapid gas shut-off cock were incorporated in the system for better control of the heat. The workpiece temperature was measured by shutting off the gas flow to the burner and using a contact pyrometer on the end of the workpiece tube. The tool dynamometer and machine were insulated from flame splash, heat conduction, and radiation by use of asbestos sheets. Flame heating is flexible and the capital expenditure is small. This is the reason that it is often used as the first method of heating for experimental purposes. It is severely limited though by the difficulty of localizing the heat in the workpiece when large heat inputs are required. Thus, this method is limited to low temperature work. The relatively long heating time and the difficulty of maintaining constant temperature makes this method unsuitable for production application. There is also the possibility of surface damage due to the flame or hot products of combustion playing over the newly cut surface.

ORTHOGONAL TURNING APPARATUS

Tool in Dynamometer with Thermocouple Lead, Workpiece, and Flame Heating Head

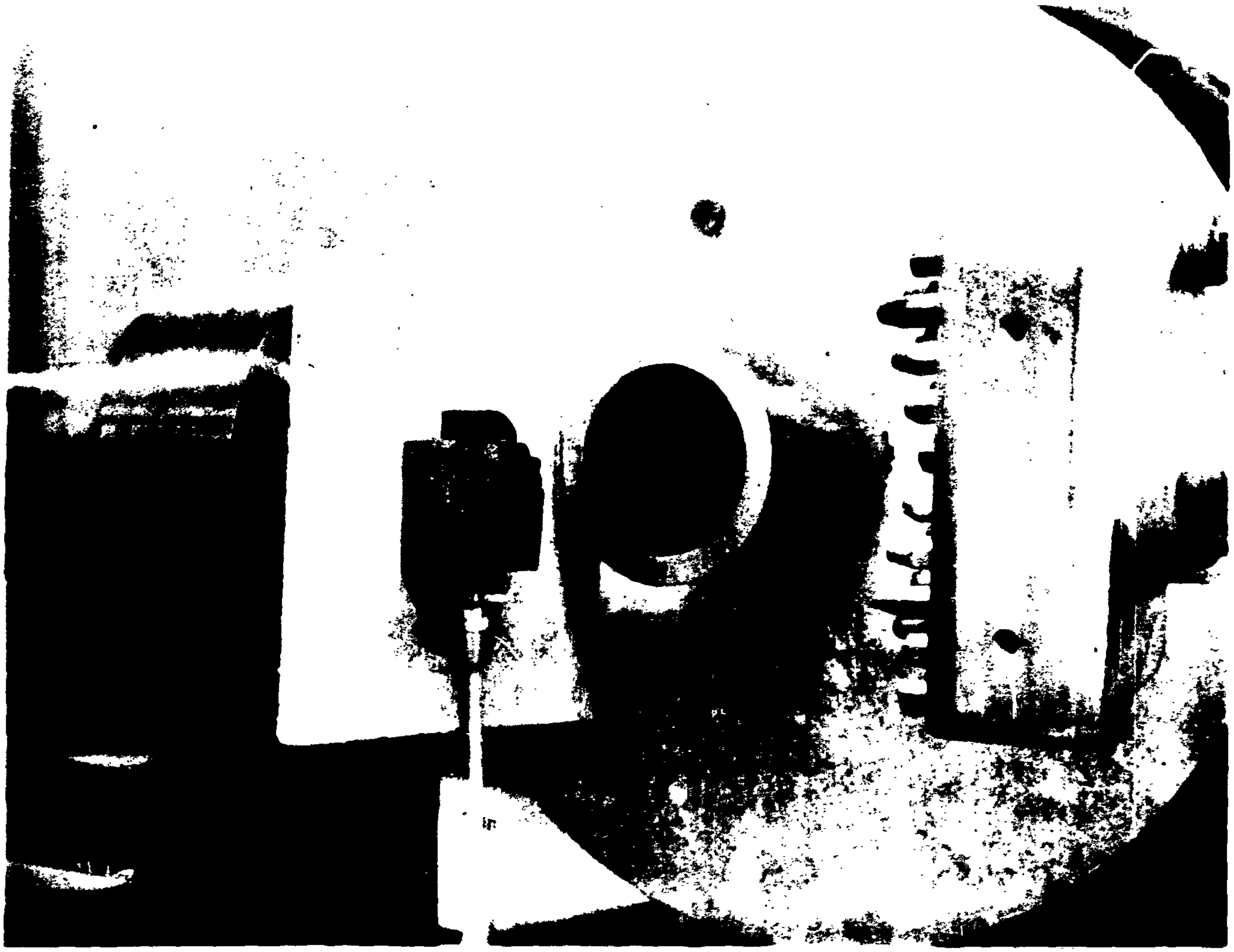


FIGURE 81

INDUCTION HEATING

Induction heating has been used quite extensively as reported in the literature and in the tests, both for milling and turning in hot machining. Inductive heating is caused by a current induced into the workpiece by transformer action. The primary of the transformer is the work coil, either around or one side of the workpiece. An alternating current (60 cps to 5 mc is generally used) is passed through this coil and the current is induced into the workpiece. The current in the workpiece produces heat which raises the temperature. The amount of current in the work that can be generated by the flux (magnetism generated by the current in the coil) is dependent upon the permeability (the conductivity of magnetic lines of force) and the resistivity (the specific resistance to electric current) of the workpiece. Both permeability and resistivity are functions of the material composition and temperature. The penetration of magnetic heating effect may be found from the formula

$$\delta = 1.98 \frac{\rho}{\mu f}$$

where δ = depth of penetration
ρ = resistivity
μ = relative permeabilitv
f = frequency in cps

For ordinary steels, theoretically, this amounts to 0.002" at 1000 KC (1 MC) or 0.020" at 10 KC, but for practical results we have .010" for 1000 KC and .040" for 10 KC.

Coil Shapes

The ideal coil for induction heating is several turns around the work at a constant distance from the work. This would be acceptable for hot machining (for surface heating) only in a lathe set-up. Even in this set-up, there are severe physical limitations. Since the gap must be kept constant (at about 1/8"), a separate coil must be made for each diameter turned. Taking two cuts on a straight cylinder would require two coils;

any complicated shape would require many more coils. Pancake coils, where the conductor is wound in a spiral, have less efficiency but are more convenient and flexible. The work in this laboratory has been done with rectangular pancake coils. These coils are made from square tubing with mitered corners. The pancake coil allows the heat to be transferred only to the areas that are to be heated. When the coil is used to heat a round workpiece, as in turning, the coil is bent to the maximum radius of the work. An example of this is shown in Figure 82. When the diameter is reduced, the center of the coil is maintained at the proper gap while the gap increases at the coil ends. Some loss of efficiency is experienced but since a greater amount of heat is transferred at the center (see Analysis of Heat Flow and Distribution), the loss is not great. The number of turns is dependent on the width of the coil since the coils are close wound. The length of the coil is dependent on impedance matching, permeability of the material at the flux density imposed, the temperature desired, and proper coil loading. These factors are so difficult to analyze that design is often done by cut-and-try methods.

Induction Apparatus

The laboratory set-up used to evaluate tool life in turning using induction heating is shown in Figure 83. Here transmission lines from the 1.2 megacycle induction heating machine are led to a distribution block from which leads are connected to a bent pancake type coil, which is mounted on a lathe carriage and travels with it during cutting, thus heating the workpiece in the zone just ahead of the cutting tool.

Evaluations were also attempted on a 10 kilocycle per second frequency induction heating machine. However, difficulties were encountered due to impedance matching on the output of the transformer to the load of the coil. Various coils were tried one of which is shown in Figure 84. An attempt was made to match the transformer to the coil by mounting the transformer on the carriage of the lathe. This may be seen in Figure 84 also. Only limited success was achieved and the subsequent development of radio-frequency resistance heating caused the abandonment of this line of approach.

Figure 85 shows a close-up view of the coil, workpiece and cutter when induction heating was used for milling tests. The workpiece was set so that there was about a 1/8 inch gap between it and the coil, as the workpiece was fed underneath the coil. Soon after the workpiece emerged from under the coil a single tooth carbide face milling cutter would mill off the top layer of material. A typical 8 inch long pancake type coil complete with mounting used in these tests is shown in Figure 86. Temperature resistant wrapping tape and asbestos sheeting prevented hot chips from short circuiting the coil windings. The coil is made of 1/4 inch square copper tubing, with miter joints at the corner, through which cooling water circulates. The amount of induced heat was controlled by varying the gap between coil and workpiece in the range 1/16 inch to 1/2 inch and by altering the power input settings available at the Inductron heating unit.

Induction heating allows high specific heat input so that high temperatures may be reached in a short time provided the work material is sufficiently magnetic. All of the heat is applied to a thin surface layer so that localization in depth of the temperature is possible. The necessary size of the coil makes localization of the area of heating difficult. Since the heating is surface heating, it might be difficult to use in some operations such as drilling or end milling. The configuration of the part could make the coil difficult to design. Temperature control is simple and the results are reproducible. The equipment is relatively expensive.

TYPICAL INDUCTION HEATING COIL

Bent to a Radius for Hot Turning

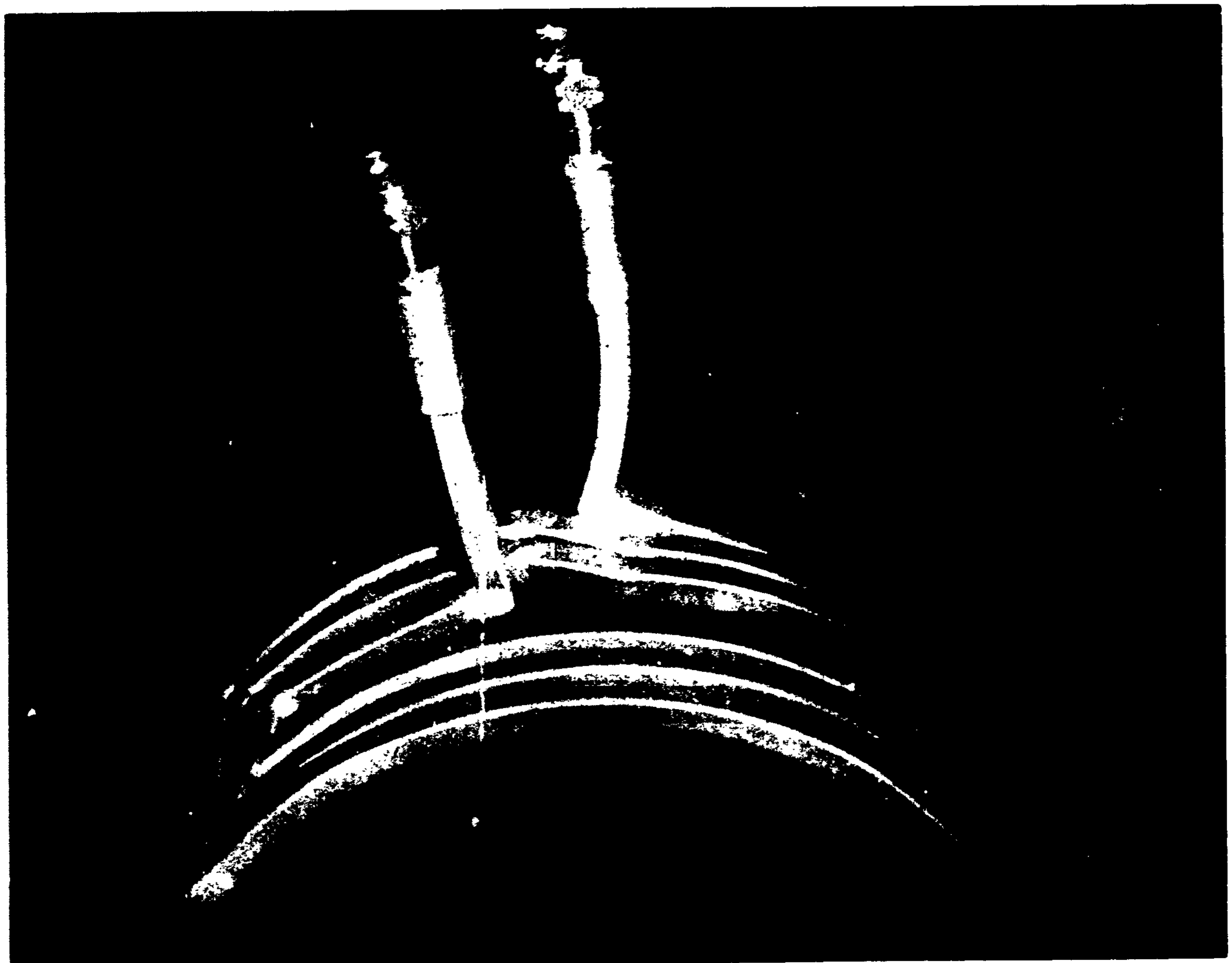


FIGURE 82

HOT TURNING APPARATUS

Water Cooled 1.2 Mc Heating Coil, Workpiece, Tool, and Radiometer Head

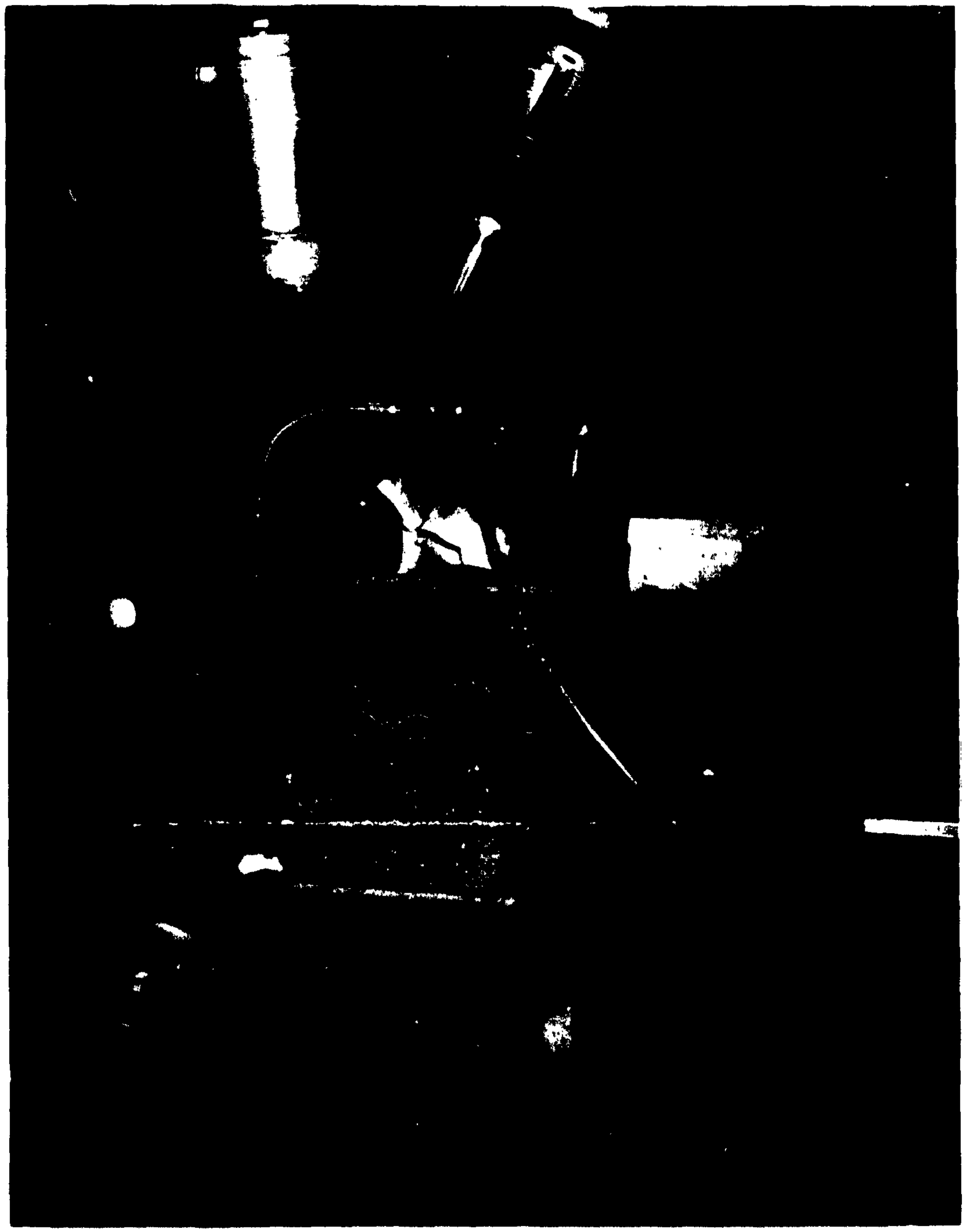


FIGURE 83

HOT TURNING APPARATUS

Lathe with 10 Kc current Transformer Connected Directly to the Heating Coil

FIGURE 84

HOT MILLING APPARATUS

Coil, Workpiece, and Cutter with Thermocouple Lead

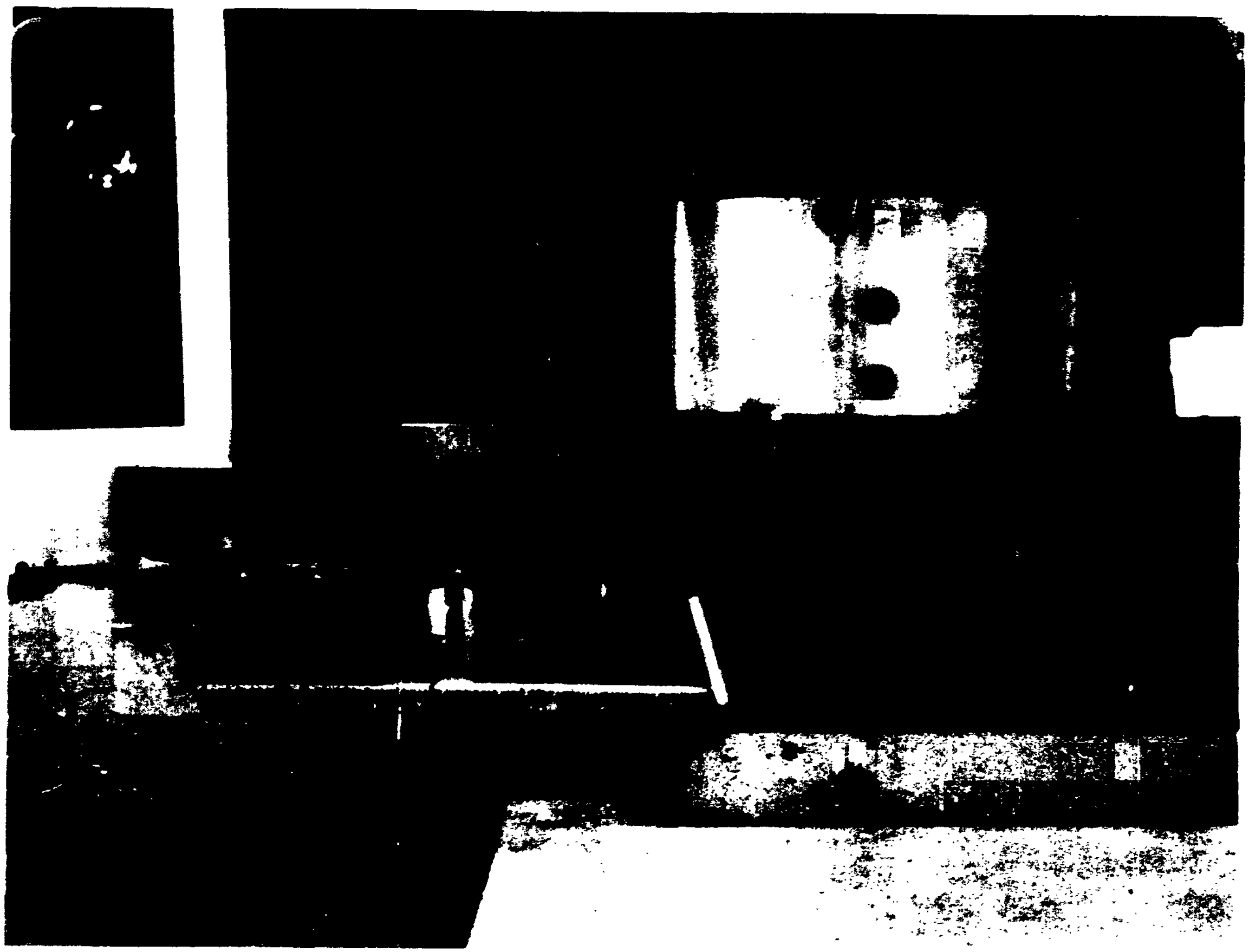


FIGURE 85

HOT MILLING APPARATUS

Typical Induction Heating Coil and Mounting

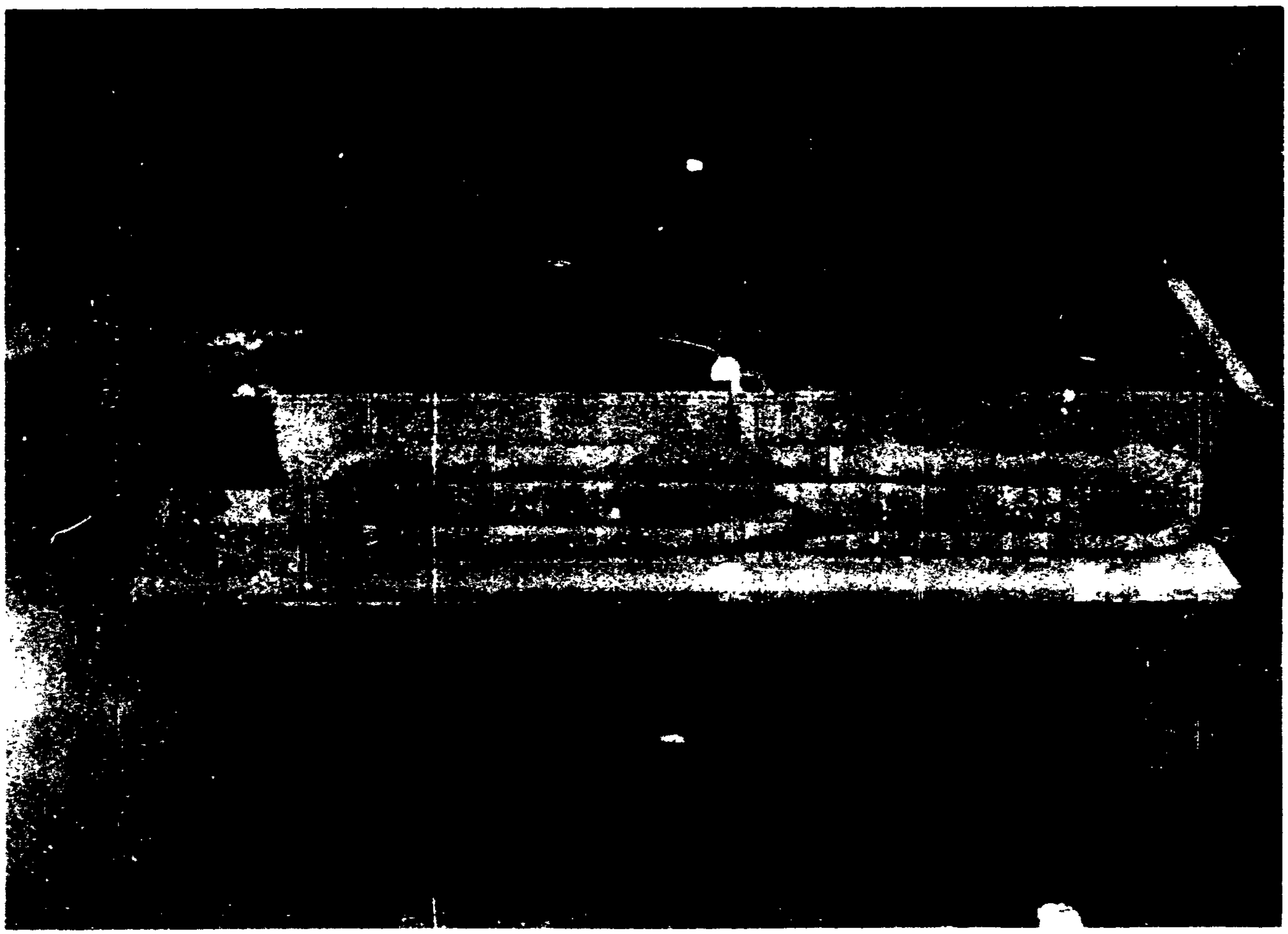


FIGURE 86

RADIO-FREQUENCY RESISTANCE HEATING

Radio-frequency resistance heating is based on the principle that radio-frequency current does not follow the path of least resistance, but rather the path of least impedance. All conductors have an inductive reactance which is added vectorally to the resistance to form the impedance. When two conductors with current flowing in opposite direction are placed side by side, a capacitive reactance is formed between them which opposes the inductive reactance in the conductors, thereby lowering the impedance. An example of this is shown in Figure 87. Here, it was necessary to heat the teeth to the sector gear. Electrodes A and B were placed in contact with the gear and RF voltage applied. The current will not flow across the straight line C, which has the lowest resistance, but instead will flow around the curve of path B, because of the lower impedance due to the capacitance between the workpiece and return conductor. This principle can be used in hot machining by passing current through the work and confining its path to a narrow line by the configuration of the return conductor. This is depicted in Figure 88 -- a schematic of the current flow when RF resistance heating is used for turning.

R. F. Resistance Heating for Turning

The initially constructed apparatus is shown in Figure 89. It shows two electrodes held in place with air cylinders and the return conductor in position to provide the low impedance path similar to that shown schematically in Figure 90. However, poor impedance matching of the generator to the load restricted the current flow and consequently low temperatures were obtained. Better impedance matching was obtained with a longer return conductor and a greater distance between the electrodes as shown in Figure 90. Both the tool and the workpiece were insulated from the machine tool to insure that no secondary path of current flow existed. Oxide tools were successfully used with this heating method to determine the tool-life cutting speed relationship at various temperatures while turning Thermold J. Difficulties were encountered however when carbide tools were used, since there seemed to be a small spark between the workpiece and the carbide tool. This spark, due to the fact that the tool and workpiece were at a different potential, caused erosion of the carbide tool. No spark occurred with the oxide tools because of their insulating properties. This problem was eliminated by attaching a small brass strip to the chipbreaker which rubbed on the workpiece to keep the workpiece at the point of contact with the tool and the tool at the same potential.

This was successfully used in determining tool life cutting speed relationship on 17-7 PH.

The good concentration and localization of heat with radio-frequency resistance heating is due to the fact that the heating is confined to a small belt approximately 1/4 inch wide around the workpiece. When compared to induction heating where the heat is added over an area 2 inches wide, it can be seen that the time for heat transfer at a given point is reduced to 1/8 under the same feed rate conditions. This reduction in heat transfer time gives a steeper temperature gradient and consequently lower temperatures in the finished part. This reduces metallurgical damage and distortion.

An improved modification of the radio-frequency resistance apparatus was used to heat the workpiece for the economic evaluation of hot machining on an aircraft truck pivot. To reduce transmission line losses, four water cooled, flexible copper conductors were connected between the Inductron and a distribution block mounted on the back of the carriage, as shown in Figure 91. These four lines were arranged in a square array such that the electrically parallel conductors were diagonally opposite each other. From the distribution block the current flowed through the return conductor to the upper electrode, through the work to the lower electrode and thence to the other half of the distribution block.

The distribution block and the electrodes were mounted on a small auxilliary carriage which was moved longitudinally by the tracer. This was necessary to maintain the proper relation between the heated area and the tool, since the 45° tracer moves the tool longitudinally when it moves in and out. The details of this carriage which also housed the mechanism for engaging the lower electrode against the work are shown in Figure 92.

The large variances in workpiece diameter present with this part would not allow the use of the simple electrode system as discussed in previous reports. A large movement of the electrode and the attached water cooled lead (common copper tubing) would flex the tubing causing embrittlement and failure. Consequently, an electrode system was designed so that the conductor was attached to a stationary copper block which was milled to provide electrical contact and serve as a guide for the movement of the electrode. This may be seen in Figure 92. The electrades were made from grade 95-20 electrical bronze to provide a low wear rate against the workpiece, and to prevent pick-up from the copper block.

Air cylinders were used to hold the electrodes against the workpiece. Low air pressure (8 psig) was used to prevent undue wear on the electrode. The upper electrode allowed a straight coupling through a piece of plastic insulator to the air cylinder, but lack of space prevented this on the lower electrode. In this case the horizontal movement from the air cylinder was pivoted through linkages to force the electrode through an insulating segment against the work. This arrangement is also shown in Figure 92.

On occasion in the past, the power was turned on before the electrodes were engaged causing minor arcing damage to the equipment and workpiece. To prevent this from happening again, a safety circuit was designed using a solenoid air valve and various relays to prevent the heating power from being turned before the electrode contacted the work. In addition, this circuit allowed the use of a limit switch to automatically turn off the power and withdraw the electrodes at the end of the cut. This was particularly helpful since the electrode must be completely withdrawn to clear the shoulder on the part but the current must be left on until the last possible instant to heat the material at the bottom of the shoulder.

Although in previous tests the workpiece and tool were insulated from the machine tool to prevent arcing at the bearings, no insulation was used for these tests. No damage to the machine tool was found.

The workpiece temperature was measured with a "Thermodot" radiation thermometer during the set-up cuts to determine the proper Inductron heating machine settings. It was focused on the area just ahead of the cutting tool. No temperature measuring equipment was used during the actual production machining, since the heat output of the Inductron could be set at the required value to maintain the workpiece temperature.

This heating method has been developed to the point that it can be expected to give good results in production run. Little special tooling is needed when straight shafts are turned with magnetic materials. Only slightly more tooling is required to taper or step shaft or tracer operation.

R.F. Resistance Heating in Milling

The R.F. resistance heating apparatus used for some of the milling tests is shown in Figure 93. The 1.2 megacycle current is fed to the electrode through the workpiece and then is returned through the return conductor. This causes the same low impedance path across the top of the workpiece. Copper tubing 3/8 inch square was used for the return conductor and the heat was, therefore, localized in a bandwidth under the tubing, as compared with 5 inch to 8 inch long pancake coils used in induction heating tests. The cutter, of course, was brought as close as possible to the heat source.

R.F. resistance heating was used when machining the "T" extrusion for economic evaluation. The heating set-up for the first two operations, i.e. machining the base and top, shown in Economics Section, was in principle identical to the original r.f. resistance heating set-up. The two electrodes are held against the workpiece with air cylinders mounted on, but insulated from, the vertical channels. The return conductor is attached to one electrode, and concentrates the heat in a controlled path just ahead of the cutter. However, on the third operation, machining the sides of the "T", it was necessary to move the electrodes toward and away from the work without moving the return conductor. In this case, the return conductor closely followed the sides of the "T" so that any lateral movement would cause the return conductor to contact the workpiece. Consequently, a design similar to that used on the truck pivot and shown in Figure 94 was developed. The return conductor was connected to a stationary copper block and the electrode moved against the workpiece by sliding in a milled slot. It should be noted that sliding contacts are easier to construct for radio frequency current than for low frequency or direct current since the energy can easily flow through the capacitor formed by the air gap resulting from the slight miss-match of parts without arcing. The return conductor was set on an angle tangent to the cutter (see Figure 95) so that all of the work would be at the same temperature when it reached the cutter.

Apparatus: The 1.2 mc heating current was again supplied by the 30 KW "Inductron" induction heating machine. Two electrodes were constructed similar to those used for face milling with provisions for easily attaching various return conductors. These electrodes are shown with the most effective return conductor in Figure 75 in the section on

"End Milling". Air cylinders are used to hold the electrodes against the work. The plastic house, which completes the cooling water circuit, was covered with braided glass fiber to provide protection from hot sharp chips.

Return conductors were constructed from 1/4 inch square copper tubing and electrolytic copper and fitted with standard tubing fittings for easy assembly. The conductors shown in Figure 96 a-g (two plates) are labeled for identification.

Return conductor "a" was similar to those used in face milling tests. It provided a low impedance path across the whole block as would be required for other types of milling.

In return conductor "b" the current flowed through the copper block and it was hoped that enough current would flow through the lip (on the left of the photo) to cause lower impedance.

The next return conductor "c" was made of copper tubing, but is of the same form as "b". All of the current was required to flow parallel but in opposite direction to the current in the work.

Conductors "d" and "e" were constructed to hold the current in the area of cut for a longer time. "d" caused the current to flow against the current in the workpiece twice and with it once. "e" also caused the current to flow against the workpiece current twice but lifted it away from the work (increased the gap) when it flowed with it.

Return conductor "f", the predescessor to the final design, passed over the workpiece with a coil gap of 7/16 inch until the center was reached; then the coil gap was reduced to 1/16 inch. This caused a low impedance current path across the entire workpiece. The current was slightly concentrated on the ends and strongly concentrated in the middle.

Return conductor "g" which was used in the end milling tests was designed for narrow workpieces and was offset so that it could be brought close to the end mill. It can be seen in Figure 75, where it is wrapped with insulating tape and attached to the electrode. Tests were also run without a return conductor for purposes of comparison.

Results: The tests were run on a 2-3/8 inch wide test piece of Thermold J at a feed rate of 3-1/2 inches per minute and a plate power input of 33 KW. After heating one half of the block the work was rapid traversed from beneath the conductor and the temperature was measured at three places with a contact pyrometer. The temperatures are shown in Figure 97 for each of the return conductors.

Discussion: It may be seen in Figure 97 that the highest temperature at the center of the block was obtained with return conductor "f". Consequently this type design, return conductor "g" which was essentially the same except with an offset, was used for the end milling tests. As was evident from the experimental results on end milling, it was possible to achieve workpiece temperature of 1000°F with this type of return conductor.

It should be further noted that in all tests the temperature at the center of the block was lower than that at the edges. This is due, it is felt, to the fact that all of the current is concentrated into a width equal to the width of the electrode, in this case 1 inch, when it is transferred to the work. This gives a larger current density times time product and consequently a higher temperature. This phenomenon was previously observed with narrow workpieces optically but no measurements were made nor any explanation offered.

The temperature shown for "no conductor" is not a general one for the whole block but is the temperature in a band where heating occurred. This band is wider and not as distinct as that obtained with return conductor "a" but it is still a band of heating. The current is concentrated into a band by two factors: 1) the band is the shortest distance between the two electrodes, 2) current in a magnetic material concentrates itself into as narrow a line as possible due to the "pinch effect".

The fact that the return conductors which reduced the impedance only in the center of the workpiece, i.e. "b", "c", "d", "e" showed little improvement over "no conductor" is perhaps due to the reduction in impedance, ΔZ, being only a small part of the total impedance, Z, of the load. In other words, when $\Delta Z/Z$ is small due to either a small change in impedance or a large total impedance the concentrating effect of the change is small and when $\Delta Z/Z$ is large, the concentration of the current is also large. In the case of the conductors "b" through "e" ΔZ was small because the effect of the conductor was only acting on part of the current path and the Z was large because the coil formed by the conductor away from the work had a large area. When conductor "a" was used, ΔZ was large, since the conductor was close to the work all the way across and Z was small because the cross-sectional area of the coil was small.

End Milling Pockets: The end milling apparatus described above was designed for heating through slots for the end milling ma h: ability tests. However, much end milling is done in pockets rather than through slots. It should not be difficult for a skilled tool engineer to design apparatus for pocket work similar to that shown in Figure 98. Here the electrodes and return conductor move in a vertical direction to contact the workpiece on its top surface ahead of the cutter in the direction of feed. When the corner is reached and heated, the heating power is turned off and the electrodes and return conductor are lifted vertically with air cylinders or other means to clear the work and the cutter is fed into the corner. Additional electrode-return conductor units can be placed in relationship to the cutter to allow feeding in different directions. The switching of the current from one electrode-return conductor unit to another with the current on is difficult, but by momentarily turning it off at its source it can be accomplished easily.

SET UP FOR HEATING THE TEETH ON A SECTOR GEAR WITH RADIO FREQUENCY RESISTANCE HEATING

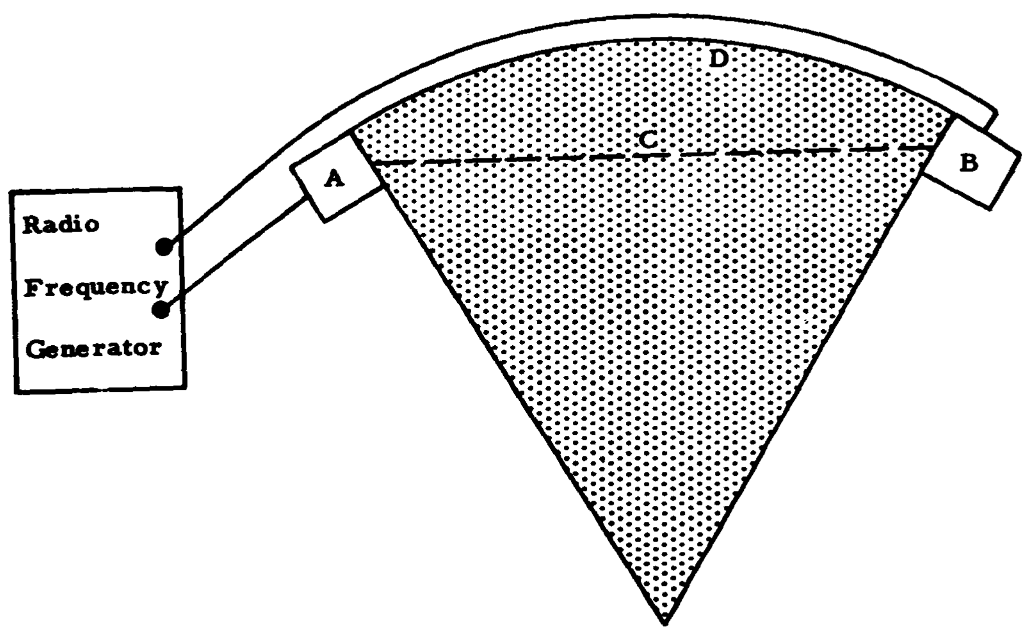


FIGURE 87

CURRENT FLOW OF RADIO FREQUENCY RESISTANCE HEATING IN TURNING

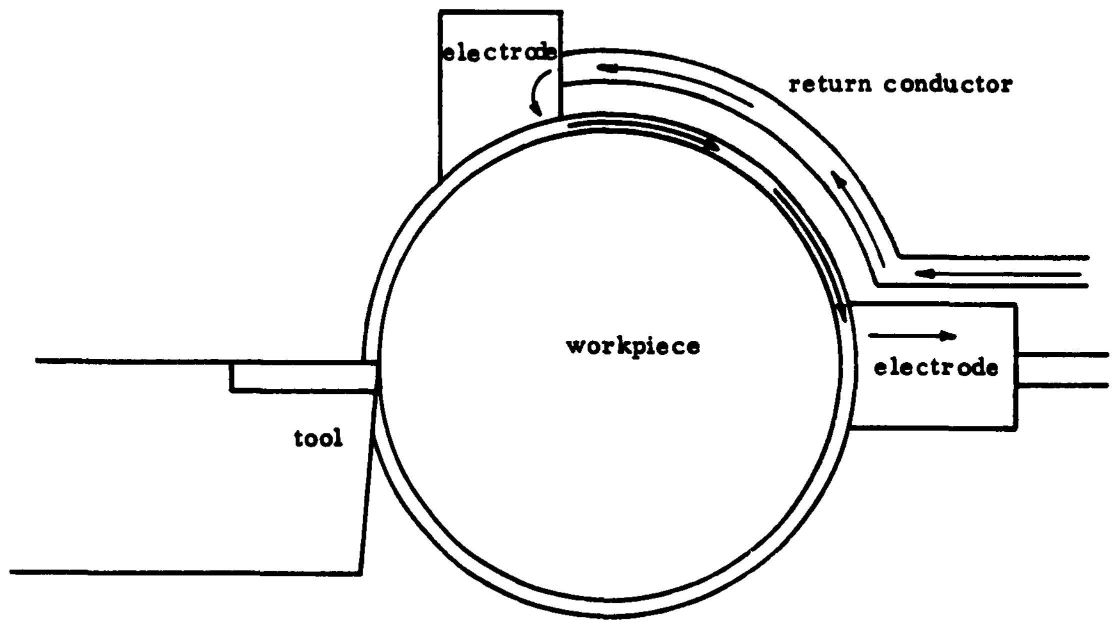


FIGURE 88

R. F. RESISTANCE HEATING FOR TURNING
Tool, Two Electrodes and Short Return Conductor

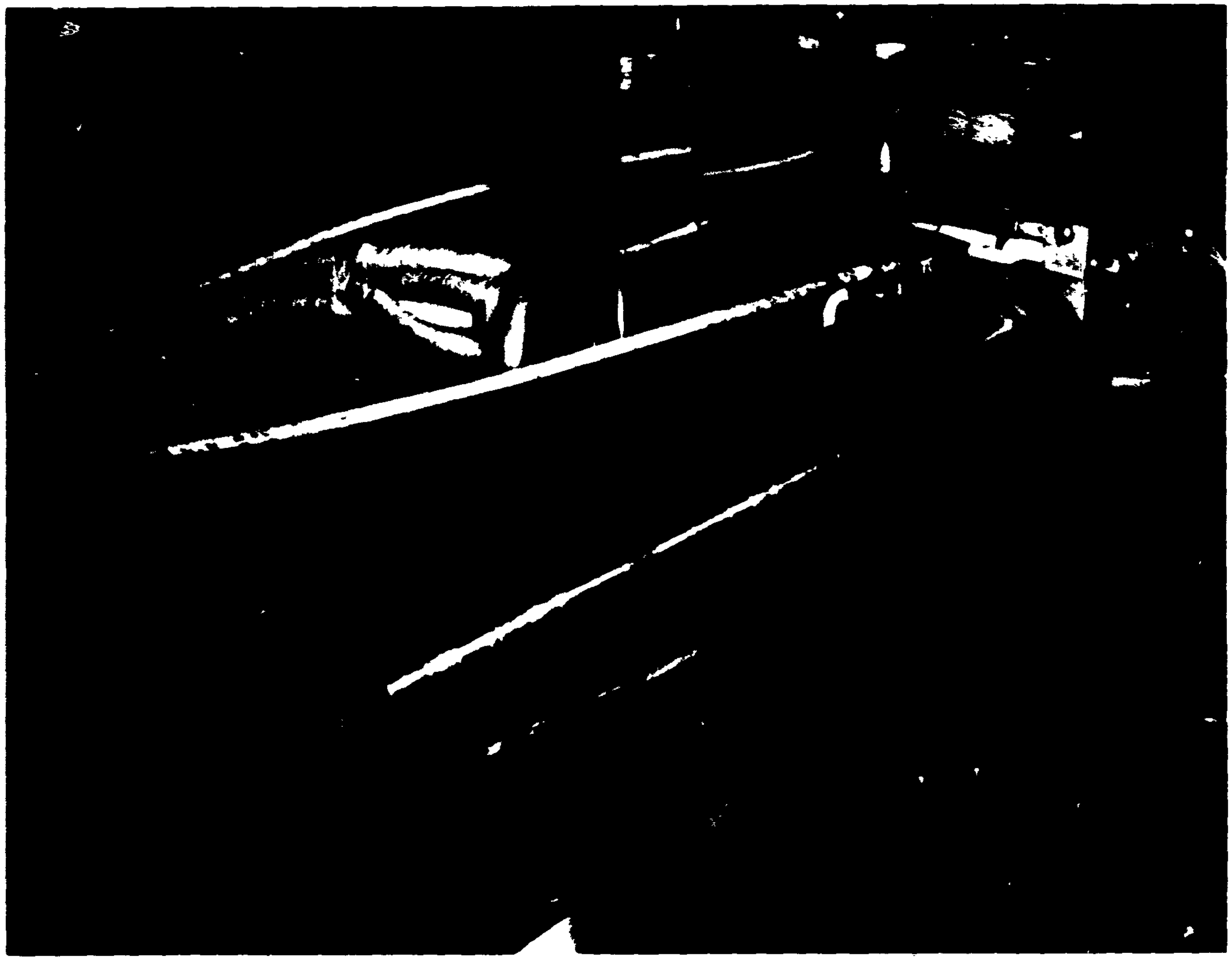


FIGURE 89

R. F. RESISTANCE HEATING FOR TURNING

Tool, Two Electrodes and Return Conductor (Tailstock is Removed)

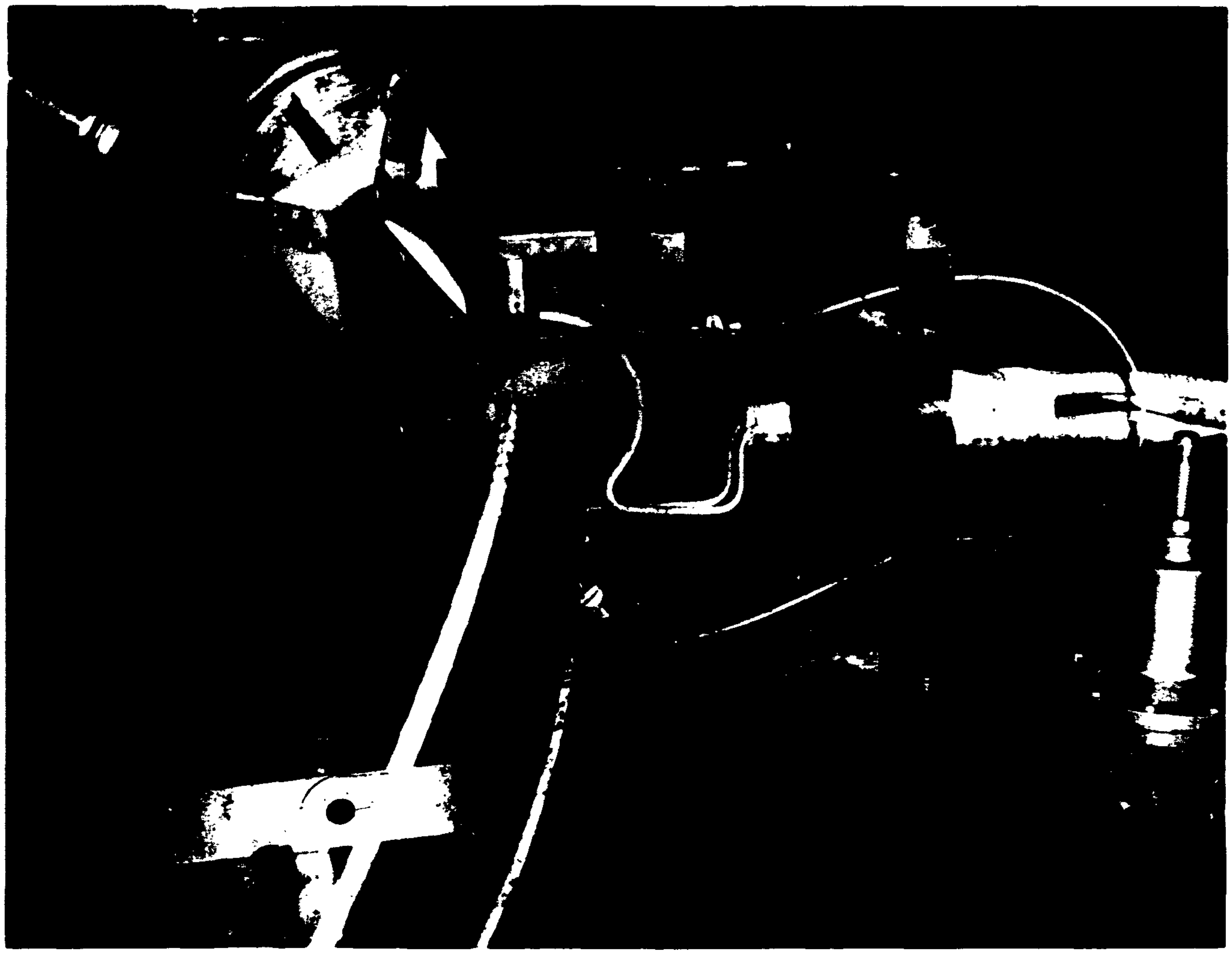


FIGURE 90

MACHINING THE TRUCK PIVOT USING R. F. RESISTANCE HEATING

Water Cooled Conductors, Return Conductor, and Electrodes

FIGURE 91

R.F. RESISTANCE HEATING OF THE TRUCK PIVOT
Supplemental Carriage and Lower Electrode

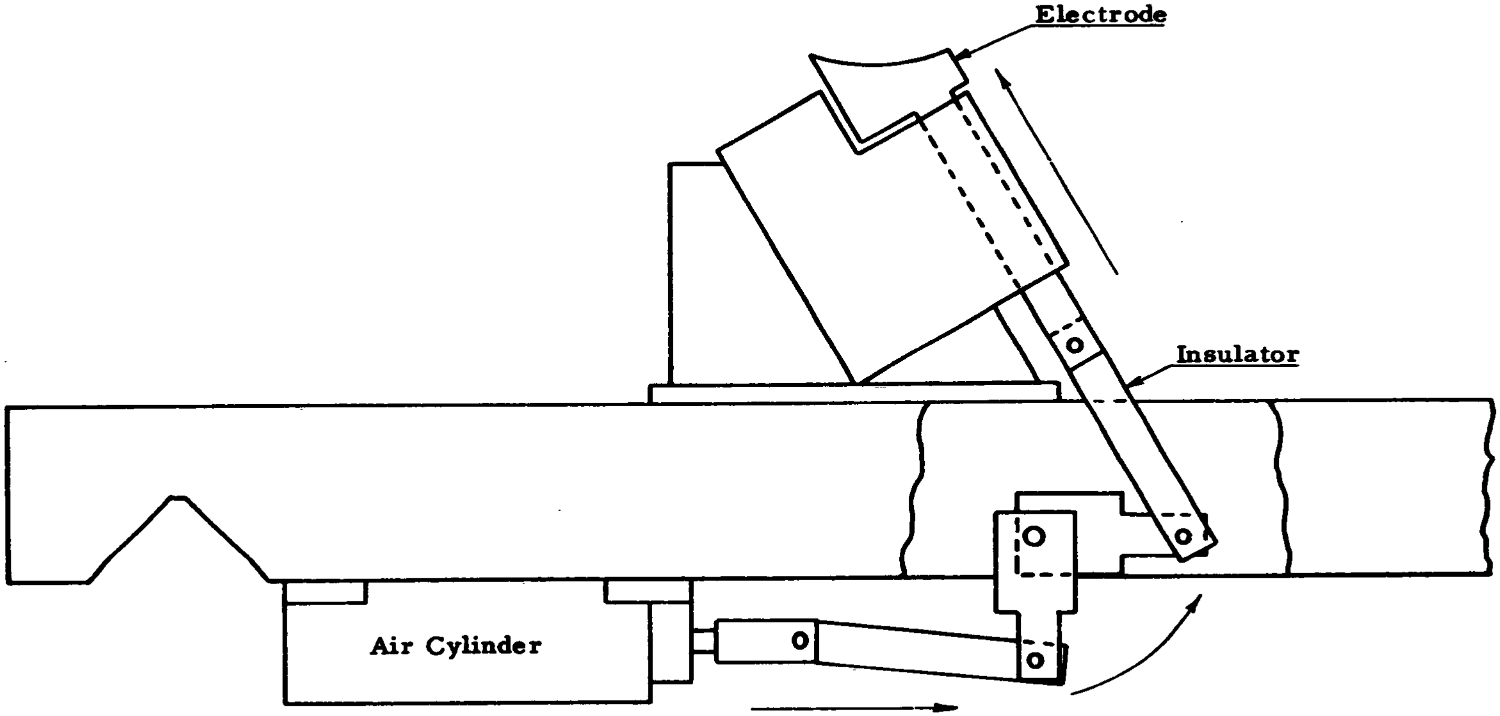


FIGURE 92

RADIO FREQUENCY RESISTANCE HEATING APPARATUS

Feed Lines, Return Conductor, Electrodes, and Air Cylinders

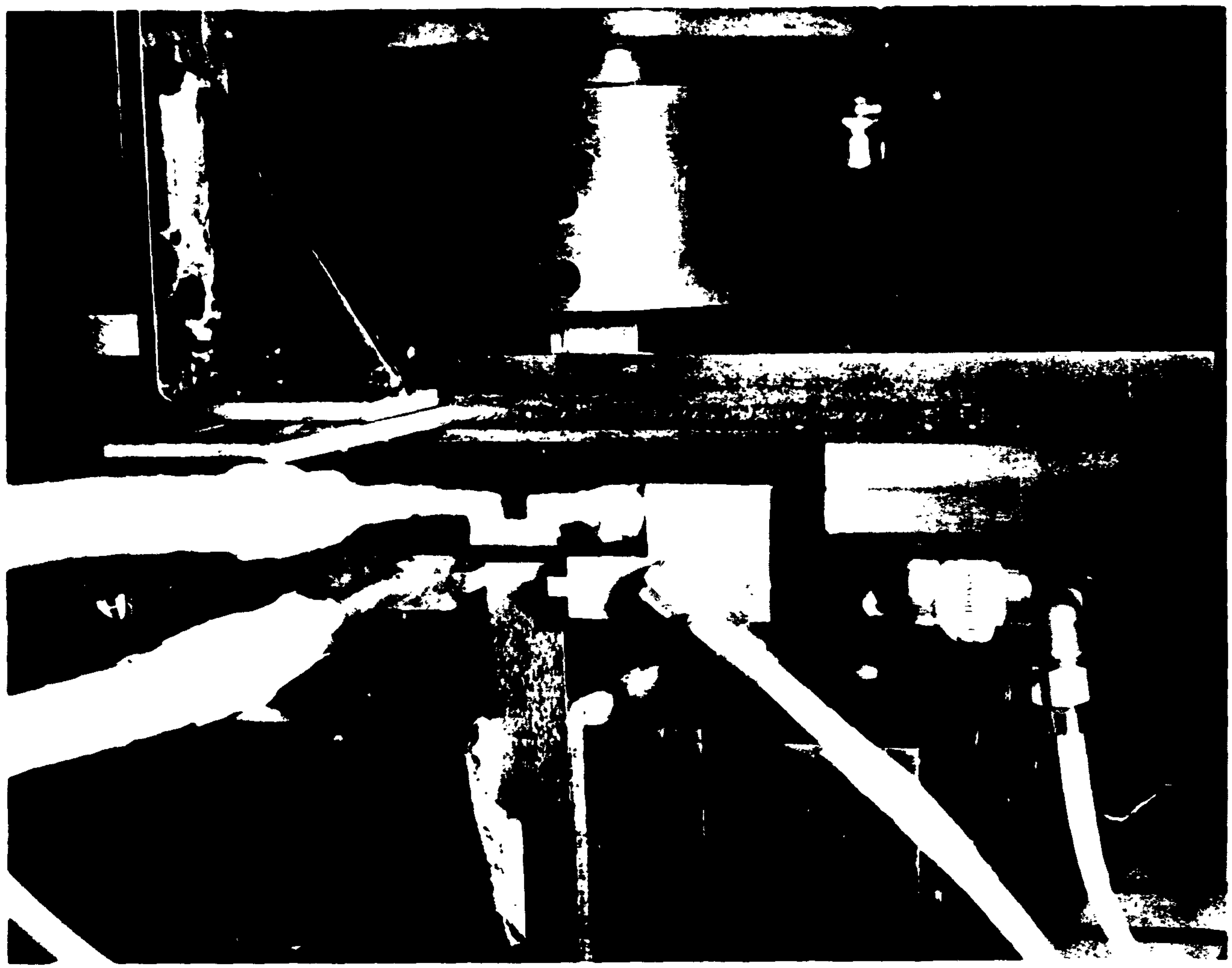


FIGURE 93

R. F. RESISTANCE HEATING OF THE EXTRUSION

Operation 3 - Machining the Sides of the "T"

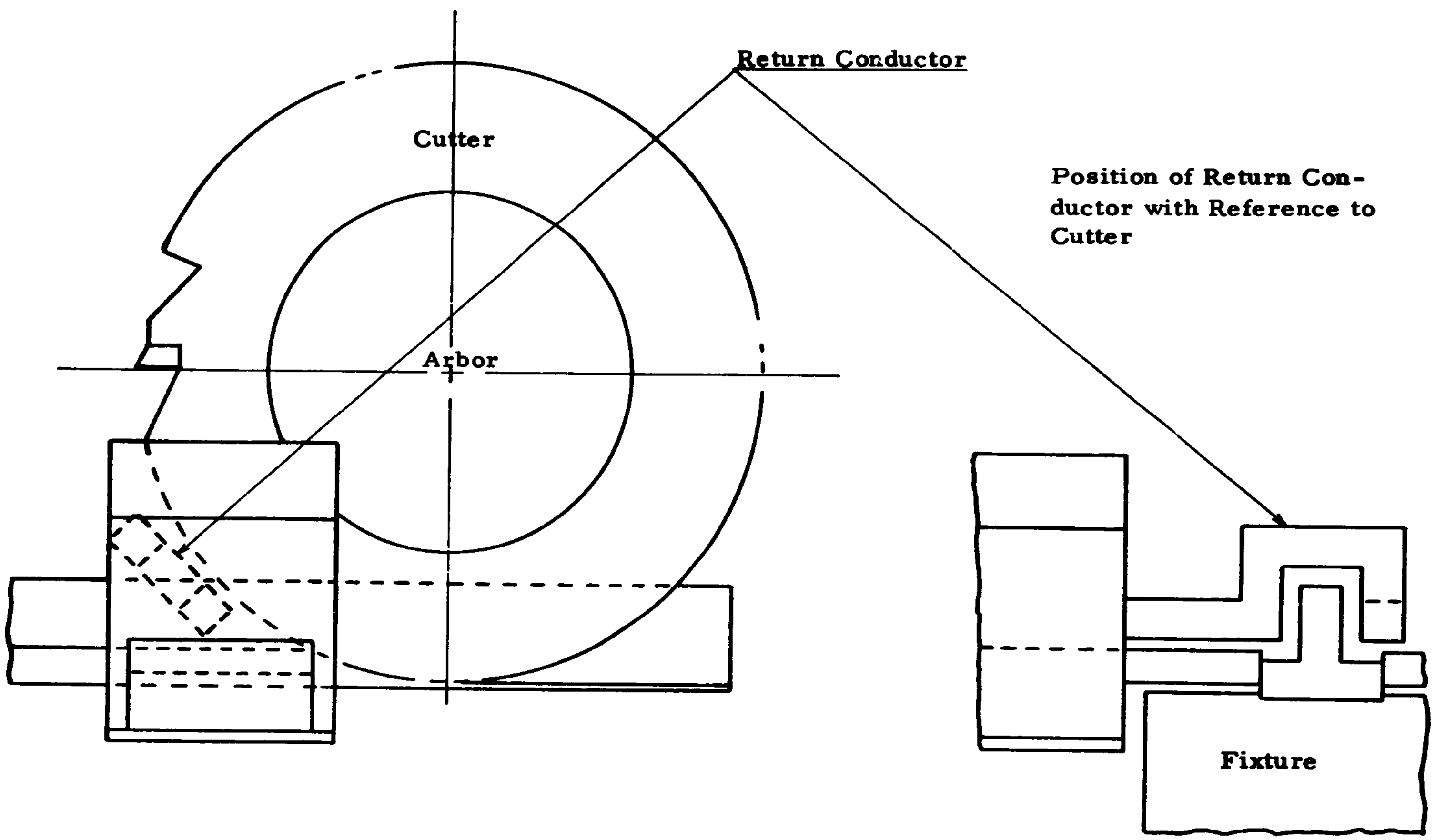
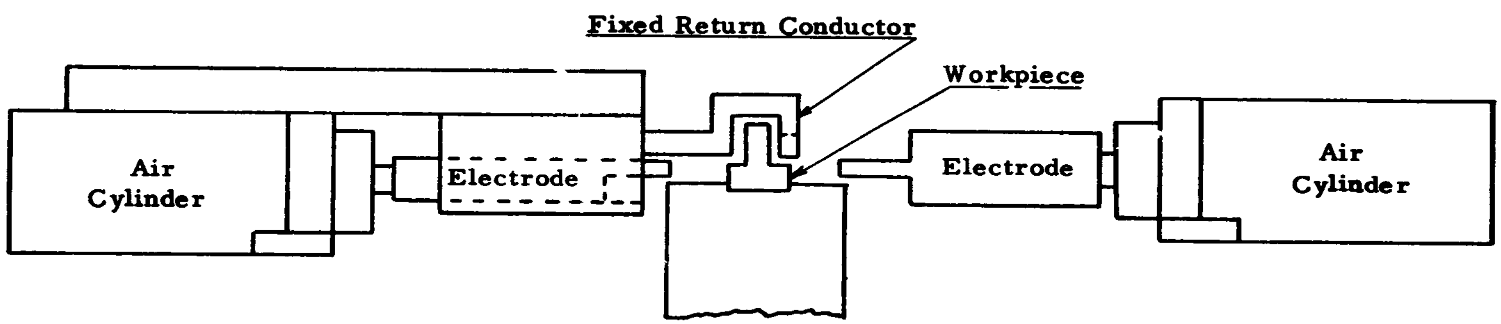


FIGURE 94

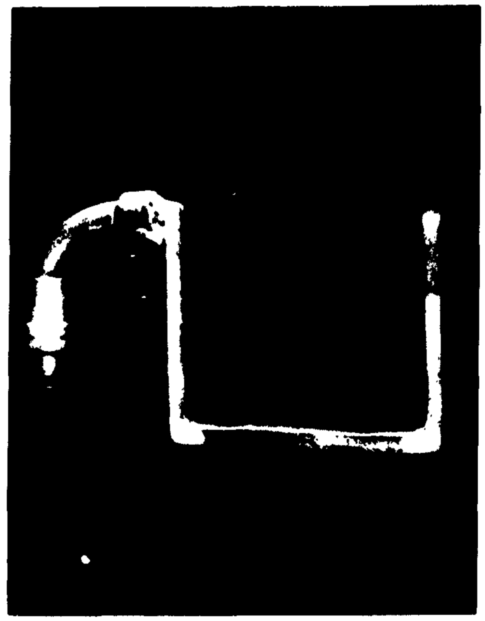
R. F. RESISTANCE HEATING OF THE EXTRUSION
Operation 3 - Machining the Sides of the "T"



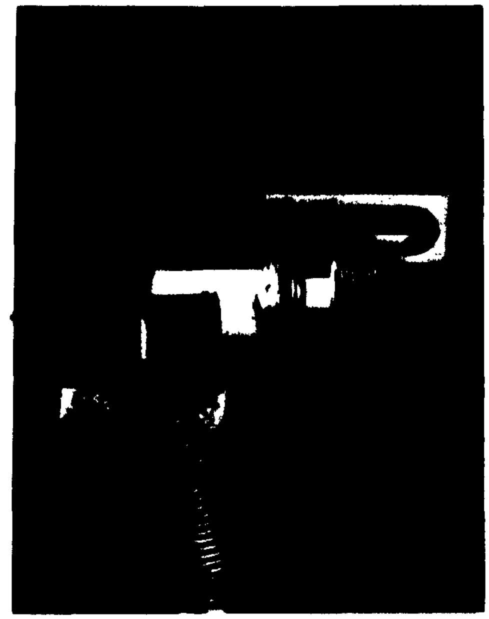
Fixed Return Conductor with Sliding Electrodes

FIGURE 95

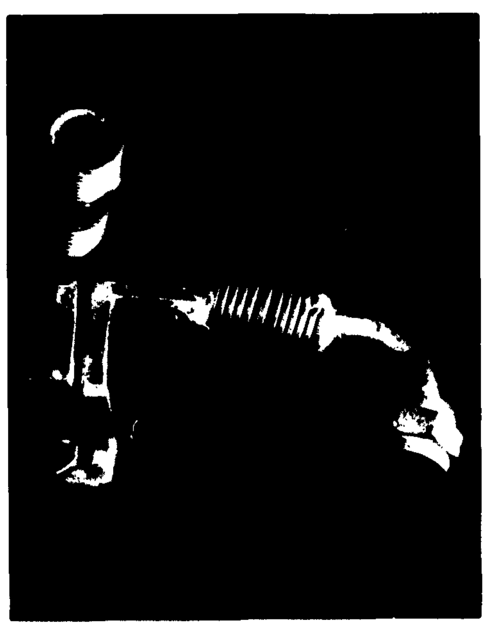
RETURN CONDUCTORS FOR R.F. RESISTANCE HEATING FOR END MILLING



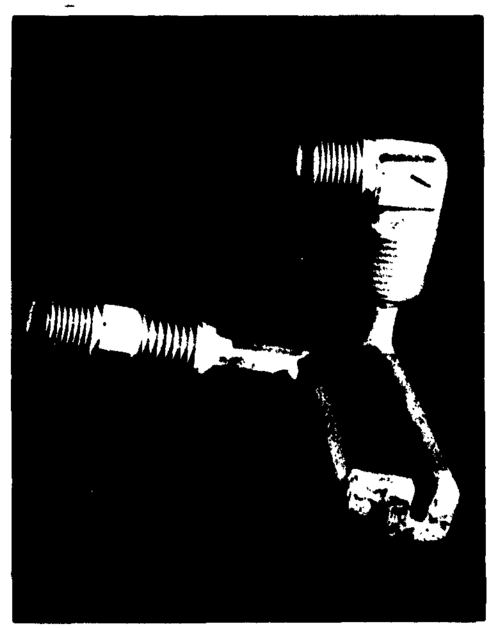
a



b



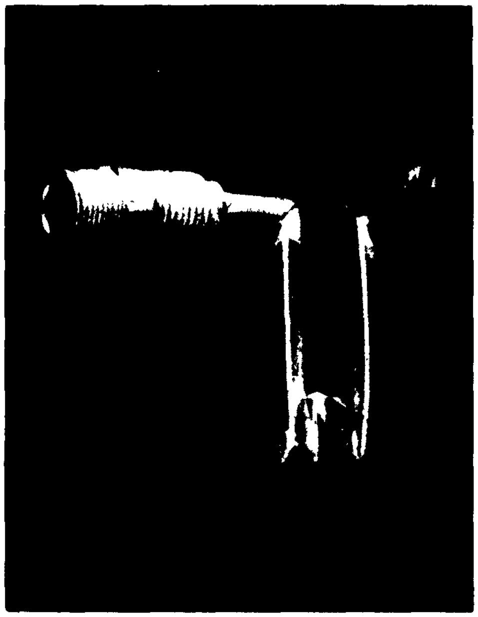
c



d

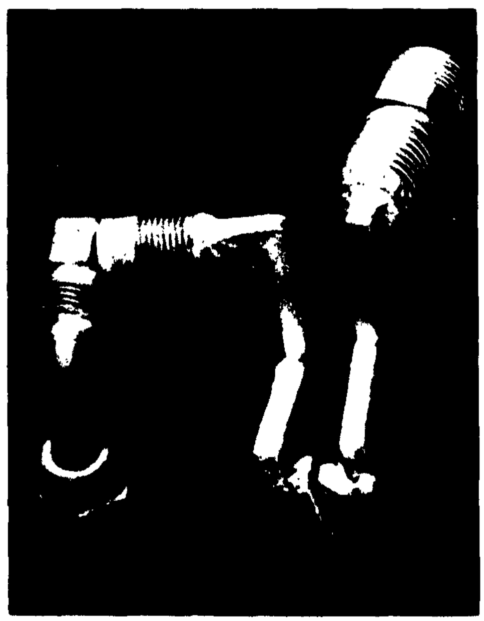
FIGURE 96 (plate one)

RETURN CONDUCTORS FOR R. F. RESISTANCE
HEATING FOR END MILLING



e

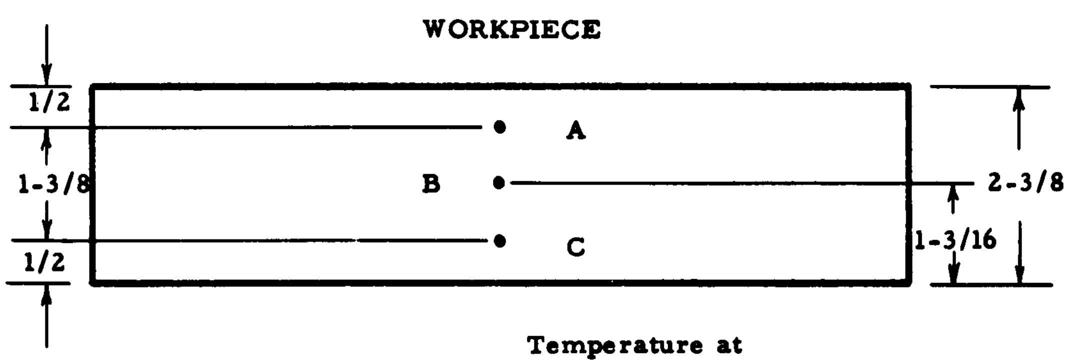
f



g

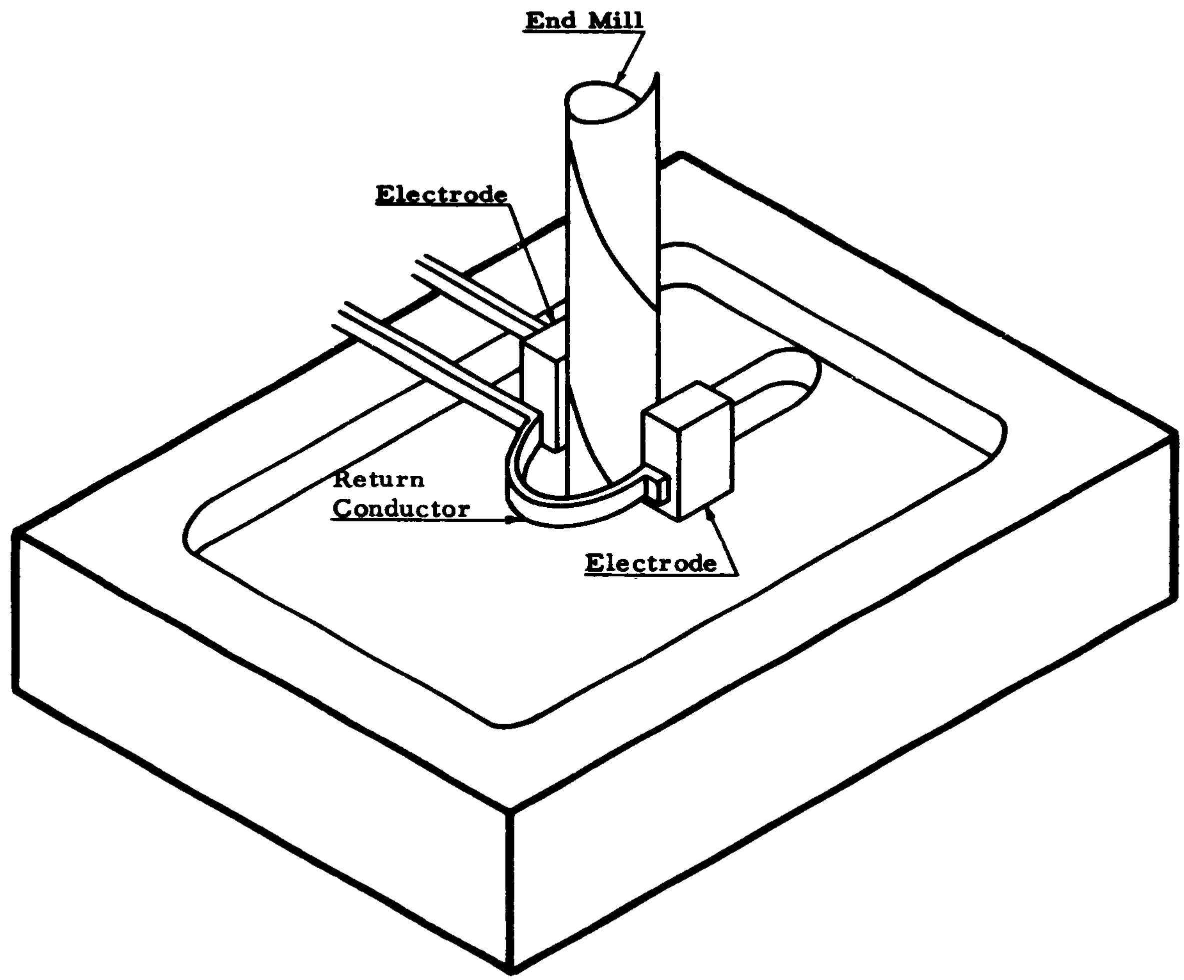
FIGURE 96A

EFFECT OF RETURN CONDUCTOR DESIGN ON TEMPERATURE



Return Conductor	Temperature at A	B	C
No conductor	440	320	500
Conductor A	530	400	510
B	400	260	430
C	370	280	440
D	490	300	520
E	500	300	530
F	575	420	560
G	520	390	500

FIGURE 97



ARTIST'S CONCEPTION - HOT END MILLING OF A POCKET WITH R.F. RESISTANCE HEATING

FIGURE 98

THROUGH-THE -TOOL R.F. RESISTANCE HEATING

It was felt that if a heating current could be introduced to the shear zone or moved close by, heating would take place only where it was required, i.e. in the zone of the plastic deformation, without heating the remaining work material with possible adverse metallurgical effect. Since radio-frequency current flows on the surface and follows the path of lowest impedance, equipment was designed to provide the current path as shown in Figure 99. The current is made to flow from the chipbreaker down the chip to the zone of shear; it then flows out past the flank of the tool to an electrode mounted below.

Initial Tests

Orthogonal cutting was chosen for the first trial because of the less complicated conditions of the chip and current flow. One water-cooled conductor was connected to a copper block, which in turn was connected to the standard chipbreaker that had been copper plated for better electrical conduction. The other lead went to the lower electrode which is held against the workpiece by an air cylinder. To keep the cooling water circulating, plastic tubing approximately 5 feet long was connected between the two electrodes to provide a high resistance path to prevent the current from passing through the cooling water. Both the tool and workpiece were insulated from the lathe with Teflon plastic to prevent arcing to the machine.

Cutting power measurements, which gave an indication of the occurrence of hot machining, were taken by a recording watt meter across the machine tool's motor terminal. Tests with sintered carbide insert cutting tools showed that hot machining was occurring. The chips became red hot. The chip type changed from discontinuous to continuous. The cutting power was reduced approximately 10% when the heating current was switched on. Tool life measurements were not practical with this set-up because of the lack of rigidity in the workpiece and tool. Cemented oxide tools were also tried with this arrangement. Complete shattering of the tip occurred when the heating power was applied. This occurred, it was felt, because the oxide tip was such a good insulator that some current arced between the chip breaker and chip instead of flowing through the tool, as was the case with the carbide tools, when the chip lost contact with the chipbreaker. Even a small spark burns a hole in the chip and this hole causes more arcing which builds up the catastrophic proportions almost instantly.

Apparatus for Conventional Turning

Because of the good possibilities shown in the above tests, it was decided to construct apparatus which could be used for conventional turning instead of orthogonal turning (see Figure 100). In this appratus the workpiece and the tool were again insulated from the machine tool. However, the tool was insulated with Micarta plastic, to give increased rigidity. The tailstock center was insulated by inserting the center into a nylon Morse taper adapter. The point of grounding was changed to the copper block on the chipbreaker. This lowered the workpiece potential to about 20 volts and the chipbreaker and consequently the chip to 0 volts. It was then possible to grasp the chip as it came out of the cut and physically guide it out of the way. Tests on this appratus again showed that hot machining was occurring, and that the heating of the workpiece was very concentrated. However, the tool shank and the carbide insert were heated to a red heat after about 3 minutes cutting. The heating pattern on the tool indicated that all of the current was not flowing down the chipbreaker to the chip, but some current flowed down the backside and underneath the holder and then up through the carbide tip to the chip. This phenomenon probably occurred in the orthogonal cutting set-up as well, but cuts were not of long enough duration for the effect to show. In addition, the presence of a high frequency alternating magnetic field caused induction heating to both the tip and the tool holder.

To eliminate this heating of the holder, a tool holder was constructed of non-magnetic stainless steel. However, this holder was not strong enough to take the high cutting forces experienced and consequently failed. A tool holder having the necessary strength and low magnetic permeability was constructed of Rene' 41. That this tool holder did not heat showed that the heating was due, at least in part, to induction of the magnetic field. However, again the cemented carbide inserts were heated to red heat by induction heat, by the induction heating of the cobalt binder and resistance heating due to current passing through the insert. Less magnetic carbide inserts such as grades K6 and K165 (permeabilities of 1.5 and 1.25) gave indication of less induction heating, but the induced tool temperature when coupled with the high interface temperature when cutting these materials caused the tool to fail rapidly.

The only non-magnetic tool material presently available commercially is aluminum oxide, and oxide or ceramic tools have little resistance to energy shock, whether mechanical or thermal. When the chip is sliding across the chipbreaker, the electrode, from which the current is transferred to the chip, does not contact the chipbreaker in the same spot or with the same pressure at all times. Indeed, it may even lift from the chipbreaker due to the cyclical nature of the chip formation. This causes a sharp change in the temperature or energy level of the chip, which, if not limited, results in immediate catastrophic failure of the cutting edge of the tool. By providing an alternate path of greater impedance through which the current may flow when intimate contact between the chip and chipbreaker is broken, in the form of a brass strip connected to the chipbreaker and riding on the workpiece (see Figure 100), this energy chock is significantly reduced. This did not, unfortunately, eliminate the surges. When tool life tests were run, the tool life without heating was longer than that obtained when the heating power was on. If a tool was removed after operating for a short time with the power applied and examined under a microscope, slight cracks perpendicular to the cutting edge were observed. These cracks would, after further cutting, increase in size and cause chipping and rapid failure to the edge. Several different types, but not the complete spectrum of oxide tools, were tried in an effort to find one that had greater resistance to energy shock. None of them however, were able to cut the material, 600 BHN Thermold J, at room temperature. Catastrophic failure occurred so fast upon engagement with the 600 BHN workpiece that the heating power could not be turned on. It appears therefore that the solution to this problem will be to eliminate or reduce the shock to levels where the oxide tools can withstand them.

Through-the-Drill R.F. Resistance Heating

Since through-the-tool heating gave good concentration of the heat in the shear zone, it was felt that this method of heating might be used in drilling, the most difficult hot machining operation.

Apparatus: Apparatus was designed to pass the radio-frequency alternating current through an electrode to the drill and down the drill to the chip and the chip forming shear zone.

The apparatus was set up on the lathe with the drill stationary and the work rotating. The radio frequency heating power was again supplied by the 30 KW, 1.2 mc "Inductron". Figure 101 shows one water-cooled electrode clamped to the 1/2 inch drill and the other electrode held against the cylindrical workpiece. The drill holding fixture was attached to the carriage to give positive feed. The tailstock of the lathe was also fastened to the carriage so that the center could be used to absorb the thrust force from the drill. The electrode on the drill was grounded to give an electrically cold chip. The HSS drill was copper plated to give a lower electrical resistance.

Results: The through-the-drill R.F. resistance apparatus gave excellent results upon immediate entrance of the drill into the cut. At this point the heat was concentrated at the zone of shear and the chip was continuous and hot, indicating that hot machining was occurring. However, as the hole was drilled deeper, the radio-frequency current, which likes to flow on the surface of a conductor, left the drill through the margins as the drill entered the hole. This caused arcing and softening of the margins and rapid failure from spark erosion and abrasive wear.

Through-the-Drill D. C. Resistance Heating

Because of the difficulties encountered with R. F. current, an attempt was made to use direct current which takes the shortest path instead of flowing on the surface. The direct current would flow down into the hole and consequently into the shear zone instead of arcing from the margins to the surface.

Apparatus: The lathe was again used as a drilling machine, but the power was supplied by a 400 ampere direct current motor-generator. The second water-cooled electrode was modified to permit the use of a rectangular workpiece as shown in Figure 102.

Results: When the apparatus was used with 1/2 inch drills the 400 ampere current was insufficient to heat the work material appreciably, since the large area of the chip did not provide enough resistance. When a 1/8 inch drill was used the current was sufficient to heat the chip at the shear zone, but the drill was too small to carry the required current. If carbide drills were used, more heat would be generated in the drill due to the lower conductivity, and while it would be insufficient to melt the carbide, it would in all probability cause rapid breakdown of the cutting edge.

IDEAL CURRENT FLOW IN THROUGH-THE-TOOL RESISTANCE HEATING

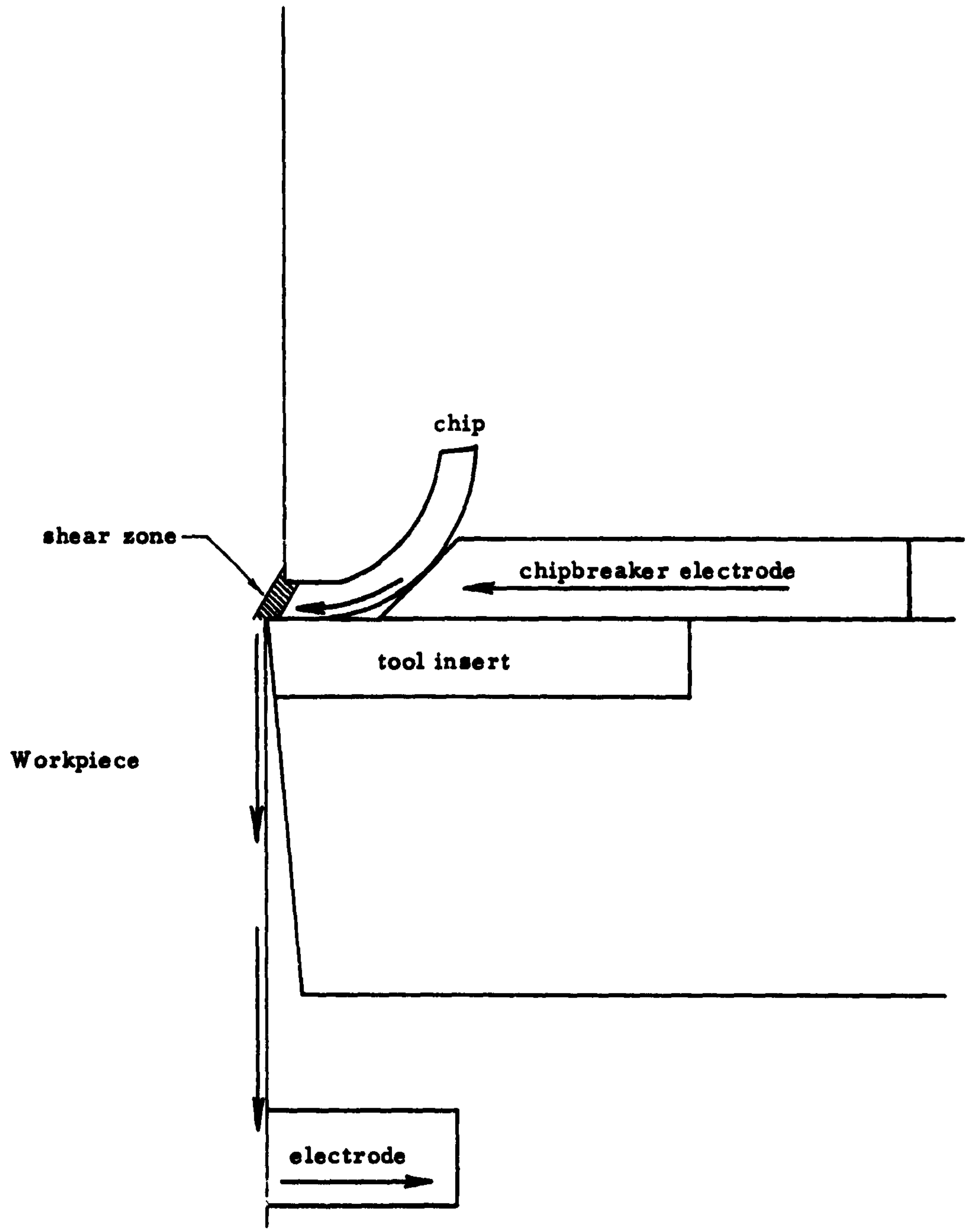


FIGURE 99

THROUGH-THE-TOOL R.F. RESISTANCE HEATING

Brass Secondary Path, Chipbreaker-electrode, Second Electrode

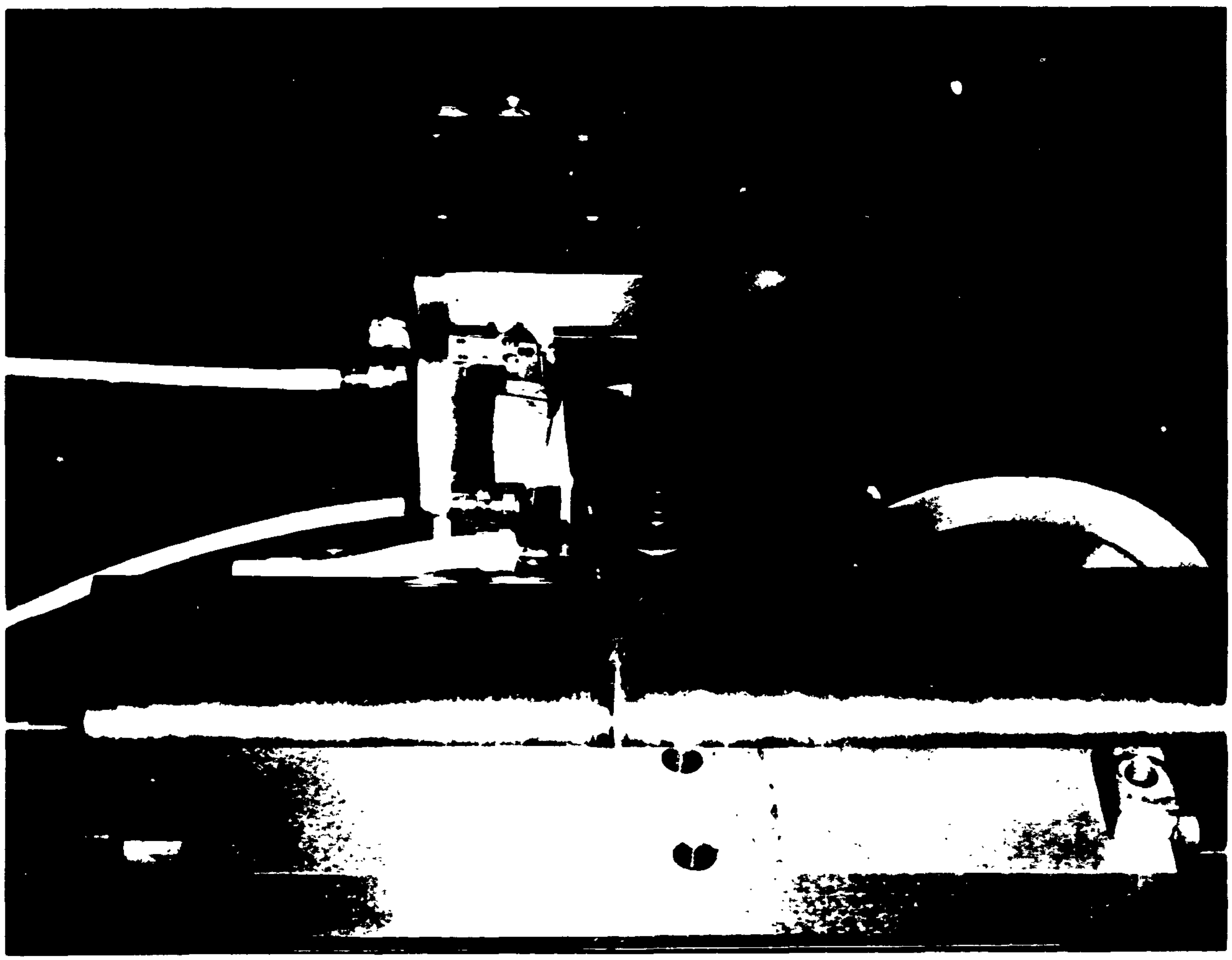


FIGURE 100

THROUGH-THE-DRILL R. F. RESISTANCE HEATING APPARATUS
Workpiece, Electrodes, Drill and Drill Fixture

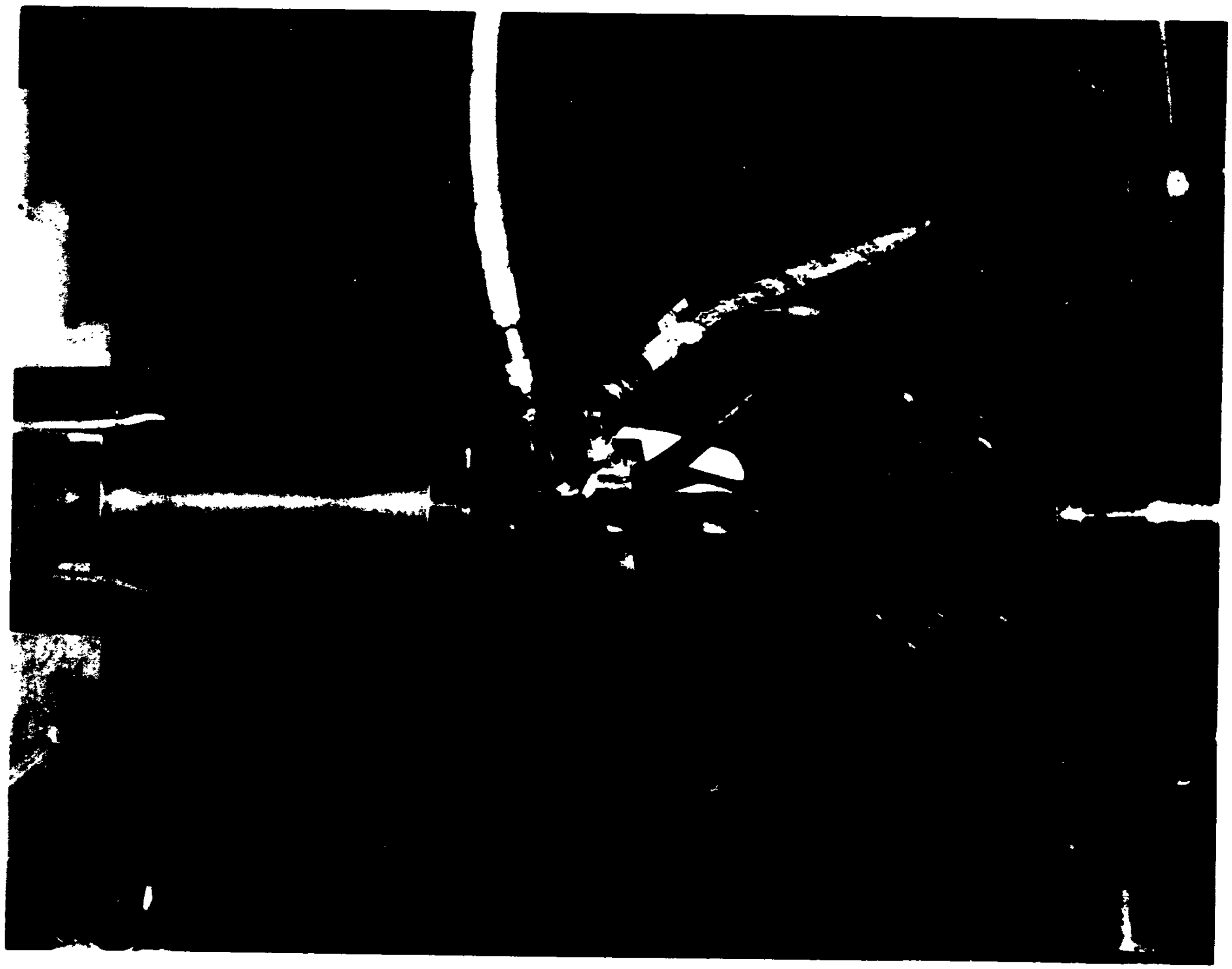


FIGURE 101

THROUGH-THE-DRILL D. C. RESISTANCE HEATING APPARATUS

Workpiece, Electrodes, Drill and Drill Fixture

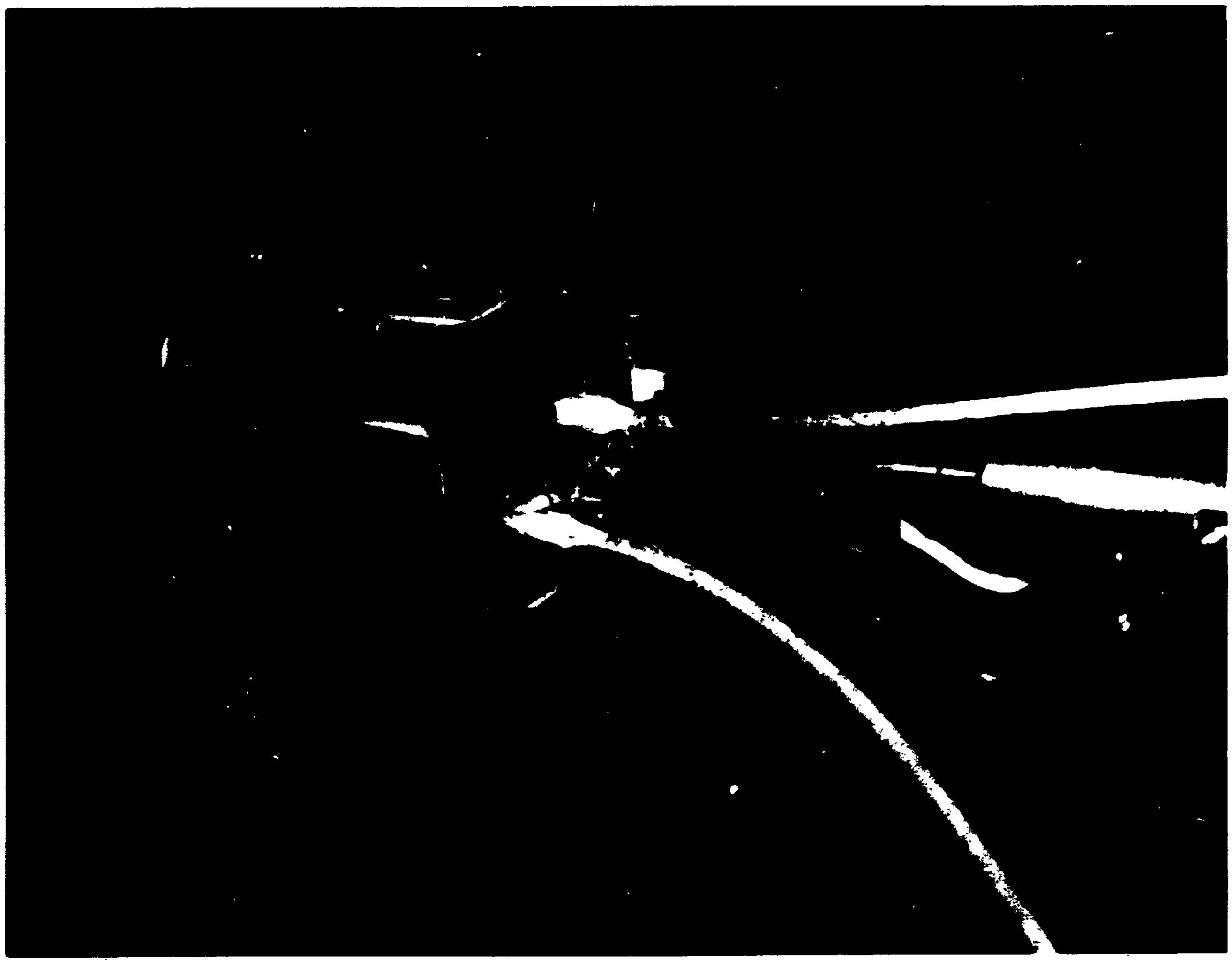


FIGURE 102

INERT TUNGSTEN ARC HEATING

The various heating methods using radio-frequency current have proved most satisfactory for heating magnetic materials to temperatures around 1000°F. However, when materials of low permeability (non-magnetic) are to be heated they are not effective. In addition, the cobalt and nickel base alloys must be heated to much higher temperatures (around 2000°F) to achieve optimum machinability. After considering the various heating methods that did not depend on magnetic permeability, it was decided to construct an inert tungsten arc heating apparatus. It was felt that the disadvantages of arc heating could be surmounted or minimized by careful design to allow the successful use of this method. Proper shielding from the radiation of the arc must be provided to prevent sunburn and eye damage to the operator. The arc current and voltage and the gas flow rate must be measured and held constant to maintain even heating.

Apparatus

The inert arc heating apparatus was designed to heat a one inch wide face milling workpiece. The torch which was designed to conform with space limitations is shown in a sectioned drawing in Figure 103. It consists of a copper body enclosing an insulating filler of "Micarta" and a copper collet holder. The electrical connection is also insulated from the copper body to prevent the danger of electrical shocks. A small copper tube is soldered to the body to deliver the inert shielding gas. The 2% thoriated tungsten electrode is held in a steel collet which is drawn up by the screw in the plug. The flow of gas is controlled on exit from the torch by the ceramic cup. The torch is cooled by water flowing in the copper tubing surrounding the copper body. Copper was used for many parts because its high thermal conductivity would carry off the heat. It was felt that this would be more advantageous than manufacturing the parts from temperature resistant materials. The collet holder, collet, electrode and ceramic cup were standard commercial items.

The torch is held on a special fixture which allows it to slide back and forth perpendicular to the axis of the workpiece and the feed. A "Variac" controlled motor attached to a reduction gear rotates an eccentric cam to move the torch back and forth across the work approximately 150 times per minute. The fixture is adjustable to allow the position of the workpiece to be changed in relation to the center line of the cutter in order that engagement angle might be varied and to allow the use of workpieces up to 4 inches in width. Other adjustments permit the movement of the torch closer or farther away from the cutter to increase or decrease the time for heat transfer. It was found that the torch could not be brought closer than 3/4 inch from the cutter without heating the cutter and subjecting the torch to possible damage by flying chips. To bring it this close it was necessary to incline the torch 15° to the vertical and thereby make it parallel to the corner angle of the cutter. The special fixture is shown in Figure 104.

Shielding consisted of a piece of fiber board mounted on the side of the machine table. The shield was higher than the arc and extended the whole length of the table. It did not allow the operator to stand beside the arc but protected him when he was operating the machine. By stepping to the side he could stand behind and be protected by the cutter and milling head. Screens were erected around the machine to protect the eyes of those working in the vicinity. When the operator examined the arc he wore a standard welding hood. For production operations a more elaborate shield could be constructed which would completely enclose the arc and have dark glass windows for inspecting the process.

Power for the arc was supplied by a 400 amp, direct current, welding machine. Any welding machine can be used which has an open circuit voltage of 90-105 volts D.C. The machine must have sufficient capacity to carry the load at 100% duty cycle since the current will be applied for a long time. Number 00 stranded copper cable was used to provide sufficient current capacity with the required flexibility. A starting switch type relay was installed to turn the current on and off without switching the entire heating current. The controlling switch for the relay was mounted on the fixture to allow easy access in case of an emergency.

A more sophisticated and advanced unit was designed where a Linde "Heliarc" torch replaced the specially designed torch used previously and a new oscillating unit was constructed. The oscillating unit, shown in Figure 105, which moves the torch back and forth across the workpiece for even heating, consists of an eccentric driven through a flexible shaft which moves the torch holder along a track. The motor is mounted on top of the milling machine where it is out of the way and is controlled by an on-off switch mounted on the table.

The inert gas for shielding the electrode was provided by a standard cylinder and metered by a combination pressure reducer - flow meter. When exact measurement of the flow rate is not required, a standard welding type oxygen pressure regulation could be used.

Argon gas was used to start the arc and then a mixture of argon with 35% hydrogen was used. This was done to obtain the maximum power and still make starting easy. Since the heat obtained from the arc is a product of the voltage and current, and the current is limited by the capacity of the welder, it is imperative that a sufficiently high voltage be used. The high frequency current will not start the arc if the voltage required to bridge the arc is more than 25 V (about a 5/8 inch gap with argon). Therefore, the arc is started in argon with a gap requiring 25 V. Then the 35% hydrogen is added which increases the voltage across the same gap to 40 volts.

Heating tests were conducted on a block of Rene' 41 to determine the work temperature -- heating power relationship as shown in Figure 106.

A test block was constructed with an imbedded thermocouple 1/16 inch from the surface. The thermocouple was connected through a potentiometer which provided a bucking e.m.f. to a Brown "Electronik" high speed recorder. These tests were made to determine the temperature at which optimum tool life was obtained.

Further description of the use of the inert arc torch will be found in the Refractory Section.

Arc Operation Procedure

(1) Start inert gas flow; regulate to approximately 30 scfh

(2) Start the oscillation of the torch

(3) Turn on the arc current

(4) Commence feeding

(5) Just before the end of the cut turn off the arc current

(6) After the electrode has cooled enough to touch, turn off the gas flow.

Safety Precautions for Arc Heating

In addition to the normal safety precautions necessary for hot machining as specified on p. 215, the following precautions should be observed:

(1) All persons who may have occasion to look at the arc must wear welding hoods (goggles do not protect the face) with No. 10 filter plate.

(2) All personnel in the immediate area must wear long sleeves to prevent sunburn. If an operator's hands are explosed to the light of the arc for an appreciable time gloves must be worn.

Results

The inert tungsten arc gave highly concentrated heat adequate for machining Rene' 41. Figure 106 shows the temperature-arc power relationship at 13/16 inch per minute feed rate when argon is used as the shielding gas. It should be noted that the curve is hyperbolic as evidenced by the straight line on log-log paper; the curves of plate power vs. temperature with induction heating were also hyperbolic.

The temperature of the work is also influenced by the gas used. Under conditions where the use of argon gave temperatures of 1900°F, H-35 (a standard mixture of 65% argon and 35% hydrogen) quickly melted the workpiece. Helium, it is reported, will give even higher workpiece temperatures.

The inert tungsten arc gives good concentration of the heat in depth, but localization in the area to be heated is adversely affected by the hot gases blown into adjacent areas of the work. While this was not a serious problem with these tests it could pose some difficulties when a narrow cut such as a slot was made.

Although possible injury to personnel from the arc's radiation can be prevented, the additional shielding required impedes the operation. Thus, if other heating techniques can be used effectively, arc heating would not be recommended.

Inert Atmosphere

Most refractory materials oxidize very rapidly in air, at temperatures above this, protection must be given to the workpiece.

It was felt that the most practical method of providing this precision was to heat the material, cut it, and cool it to room temperature in an inert atmosphere. Argon gas is used as a shielding medium for the inert arc torch and it is heavier than air (it will fill a vessel like water). A tank was built on the milling machine table which would contain the vice workpiece and cutter, and filled with argon. The workpiece could then be processed without oxygen damage. When tested, the cutter acted like a fan and blew much of the argon out. To prevent the exit of argon and the entry of air a cover was built and a continual supply of argon was provided to keep the tank purged of air. This apparatus can be seen in Figure 107.

This apparatus completely prevented gross oxidation although in a few instances some minor oxidation was observed.

SECTION VIEW OF INERT TUNGSTEN ARC TORCH

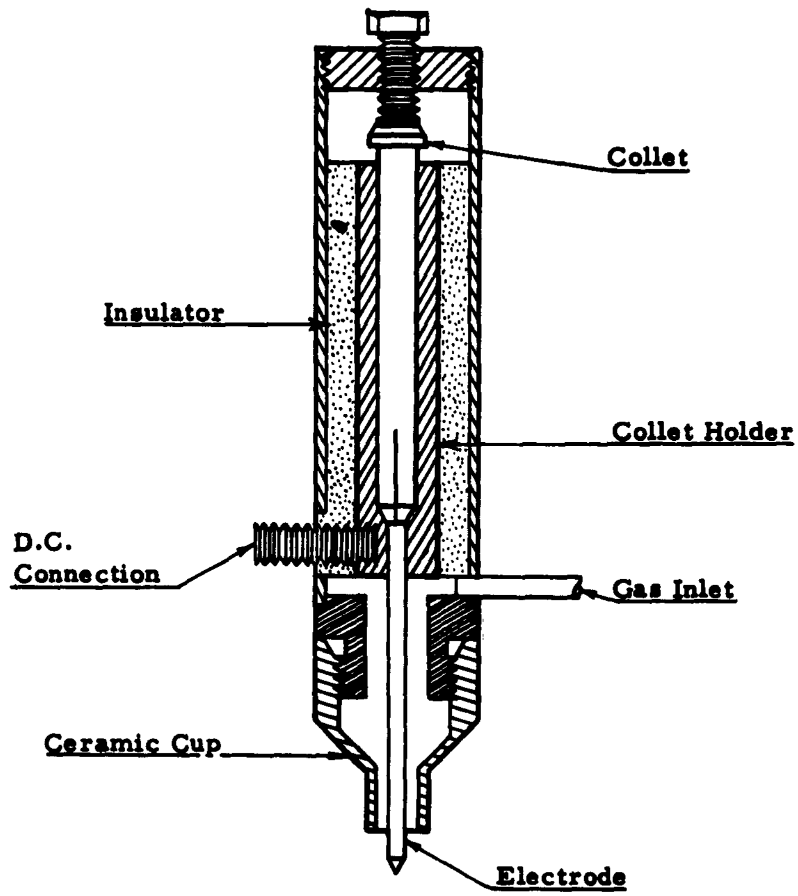


FIGURE 103

INERT TUNGSTEN ARC HEATING FOR FACE MILLING
Fixture, Cam operated Oscillator, Torch

FIGURE 104

MACHINING THE RENE' 41 WORKPIECE WITH INERT ARC HEATING

Torch, Workpiece, Cutter, Radiation Pyrometer

FIGURE 105

ARC POWER VS. TEMPERATURE

Heating Rene' 41 at 13/16 in/minute
Inert Tungsten Arc with Argon Gas

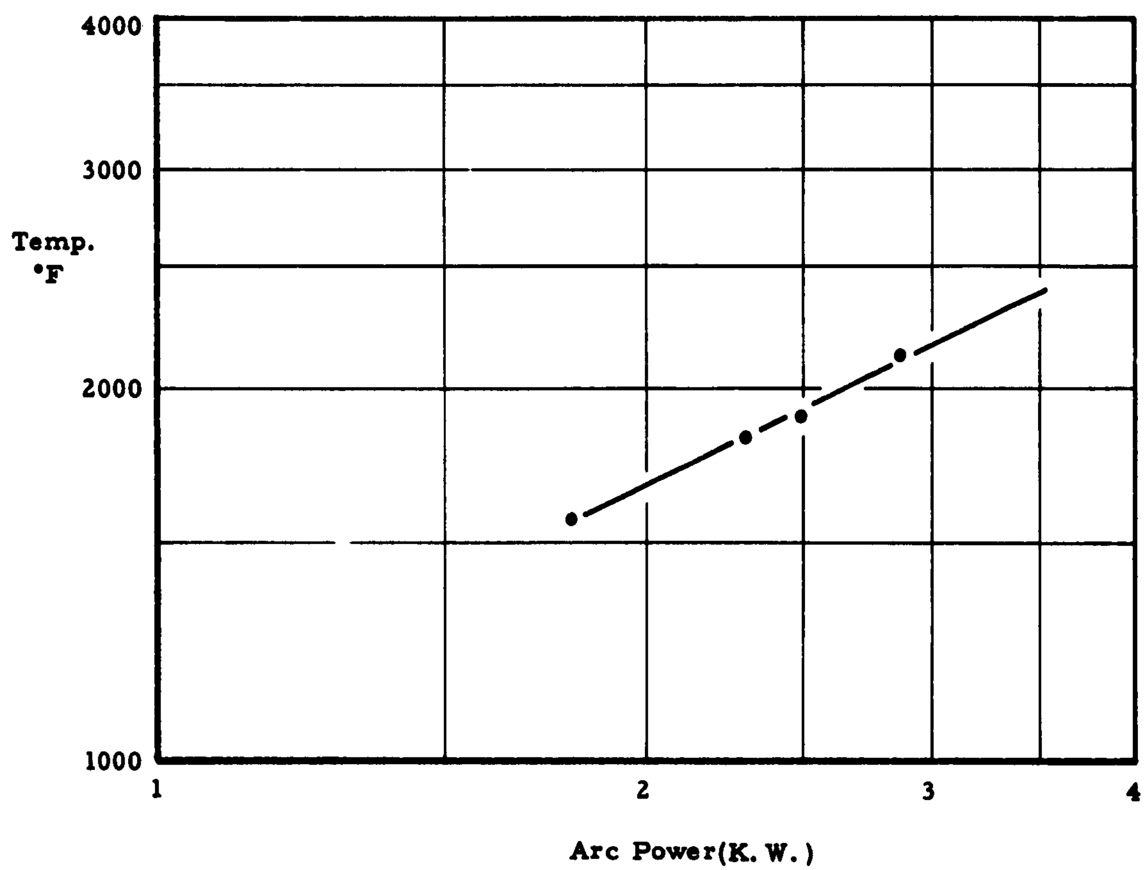


FIGURE 106

ARGON ATMOSPHERE MILLING APPARATUS
Torch, Milling Cutter and Covered Tank

FIGURE 107

MISCELLANEOUS HEATING METHODS

Radiant Beam Heating

In a patent No. 25, 105 Mr. W.W. Cargill, Jr. describes a method of radiant heating for hot machining. He uses a reflector and a lens to concentrate the energy from an arc into a small area on the workpiece. In correspondence, Mr. Cargill states that temperatures in excess of 1500°C (2732°F) were obtained in an area .155" in diameter using simple equipment but expects that this could be reduced to 30%. This method may be practical for heating refractories since it is not dependent on magnetic properties.

Preliminary calculations of power requirements for Radiant Beam Heating were made. From Figure 106 it was determined that approximately 2-1/2 KW were required to heat the 1 inch wide Rene' 41 workpiece to the optimum temperature so that the material could be cut with a 4 tooth cutter at 13/16 inch per minute. Assuming a 50% efficiency of the arc, lens and/or reflector combination a power of 5 KW is required. This may be suitable for a small laboratory test but when used under shop conditions with a 16 tooth cutter, a 3 inch wide workpiece, and the same feed per tooth 60 KW would be required.

Turning at metal removal rates of 3 to 5 cu.in/min. would require power of 15 to 20 KW for effective heating. Studies with motion picture projectors indicate that when power inputs to an arc exceed about 15 KW difficulty is encountered in arc stability. Reflector design is difficult at these power rates because cooling and the prevention of tarnishing will be serious problems.

Further correspondence from Mr. Cargill indicates that special arc techniques can allow higher power levels and that improved reflector design is being undertaken. Whether the convenience of the radiant beam heating method will offset its inherent inefficiencies and the need for cumbersome equipment remains to be explored.

Plasma Arc Heating

Plasma arc heating consists of a gas stream heated by an electric arc to temperatures as high as 40,000°F[9]. This may provide an answer to the problem of heating materials of low permeability. While some of the disadvantages of arc and flame heating are present, good control of temperature can be obtained. High heating rates give enough concentration of heat to prevent damage since these materials are relatively insensitive to heat damage. While operating costs are not high, equipment is relatively expensive and noise and glare may be troublesome.

A visit was made to Thermal Dynamics Corporation of Lebanon, N.H., a manufacturer of plasma arc equipment and discussion with their personnel indicated that the plasma arc will effectively heat the non-magnetic materials. Power supplies are available which produce more than 1000 KW at the electrode so this method will be particularly useful when large volumes of metal are to be heated at a high feed rate.

Electron-Beam Heating

A visit to the National Research Corporation of Boston to discuss the use of Electron-Beam Heating indicated that while excellent concentration and localization could be obtained with this method, insufficient power could be obtained for most machining operations. The requirements for a vacuum and the high capital expenditure required appear to make it impractical at this time.

Residual Heat

In certain sequences of operations it may be possible to machine the workpiece while it is still heated to several hundred degrees from a previous tempering or ageing heat treatment. With this method, no special equipment is required but the machine tool may be placed in an area adjacent to the heating area.

Russian Developments

Two articles[31, 50] on research in Russia report that passing electrical current through a drill or turning tool increases tool life. While the authors do not mention any temperatures or hot machining and are concerned with the current itself and its effect on tool wear, it appears that the actual process involved is hot machining. Both articles describe a variable reactor controlled transformer which supplies an electrical energy at 2 - 4 volts and 60 - 180 amps for turning with carbide tools and 400 to 1800 amps for drilling with carbide tipped drills.

It is possible that power of this magnitude will cause heating of the workpiece. It was also reported that the current caused better surface finishes and that the machined surface had a 10 - 15% increase in microhardness.

Furnace Heating

Furnace heating has been used at various times for hot machining. It involves heating the workpiece in an electric or gas furnace to the required temperature, removing the work, and then performing the machining operation while the work cools. It is a relatively inexpensive method of heating, and unless the distance between the furnace and machine is great, a simple one. This method has the advantages and disadvantages of through heating. For certain operations, such as drilling or end milling, it provides heating for the full depth of cut, but the temperature that can be used is limited to that which will cause no thermal damage to the bulk workpiece material. Since the workpiece is cooling unevenly during the operation, distortion will occur and expansion calculations (for part size) are difficult.

Resistance Heating

Resistance heating includes heating methods where alternating current (radio-frequency resistance heating will be discussed separately) is passed either through the workpiece or through heating elements embedded in the work holding fixture. In either case, the advantages and disadvantages of through heating are present. The workpiece is maintained at a constant temperature so that distortion and changes in dimensions due to cooling during cutting are not a problem. When the current is passed through the work, precautions must be taken to protect the operator and to ensure that no arcing takes place between the electrodes and work that may damage the workpiece. Temperature control is easy and accurate.

Sometimes the workpiece is covered with a molten saltbath or graphite powder to heat the block; resistance heating elements are used to heat the bath.

Radiant Heating

Radiant heating uses quartz lamps to give off infrared or heat radiation. This technique was originally developed to test missile nose cones under high temperature re-entry conditions.

The lamps may be operated at rated voltage but the power output is low so that the heating is essentially through heating. The lamps may be operated at twice the rated voltage and three times the rated power. A high enough specific heat input can be obtained this way to allow surface heating. However, under these conditions, the lamps cannot be burned continuously for more than 15 seconds or the lamps will burn out and the reflectors melt.

This method might be useful for through drilling when the disadvantages of through heating can be tolerated.

R. F. Resistance Heating for End Milling

When applied to face milling, radio-frequency resistance heating gave good concentration and localization both in the direction parallel to the feed and in depth. It was hoped that through proper design of the return conductor the concentration of heat could be localized across the workpiece as well. In such case, the current would be transferred from the contacting electrode to the workpiece and carried to the cut over a large area with consequent low current density and low temperature. As the current approached the cut, it would be concentrated to get high current density and high temperature and then, would be allowed to again flow over a large area to the second electrode.

HEAT FLOW AND DISTRIBUTION

To state that heat flow in hot machining is difficult to express mathematically is an understatement. Heisler has determined the parameters for induction or other surface heating on a heat and mass flow analyzer at Columbia University and constructed graphs to allow the determination of temperature at various times and depths beneath the heated surface.

The work done here was of empirical nature. No attempt has been made to compare the data with theoretical results.

Apparatus

In many of the tests run, the surface temperature was taken as the heating criterion. This was done because of the ease in obtaining this temperature. A contact pyrometer was used to measure the surface temperature.

To give a picture of the internal temperatures, two thermocouple set-ups were used in milling tests.

In the first test, five thermocouples were embedded through holes from the bottom to a depth of one inch below the heated surface of the workpiece in four materials. Successive depths of cuts were taken from the top and the temperature was recorded when the tool cut over the thermocouple. With each cut, the depth of the thermocouple from the heated surface was reduced until it was finally exposed. The test piece is shown in Figure 108.

Since one test piece was required for each heat input and feed rate and each test required many passes, a non-destructive test was designed. Eighteen thermocouples were embedded at various depths from 1/32 to 5/16 inch from the surface of a test block of 4340 steel as shown in Figure 109. A switch was used to scan the thermocouples and the temperatures were recorded as a function of time. Figures 110 and 111 show the set-up.

In both cases, a Weston Induction Amplifier was used with an Esterline Angus Recorder to indicate and record the temperature.

Temperature vs. Work Material

Four test blocks were made, each with five embedded thermocouples one inch from the surface, from the four materials, AISI 4340, 17-4 MO, 17-7 PH, and Thermold J. A plate power input of 27 KW was provided by the H-1 Inductron heat setting and a 1/8" coil gap. The coil was placed over the starting end of the workpiece and pre-heated for one minute before the traversing commenced. The table feed rate was 4-1/2 inches per minute and the temperature was recorded when the tool passed over the thermocouple about 14 seconds after the coil had passed. The results are shown on Figures 112, 113, 114, and 155.

The irregularities of the pattern of isotherms on the right end of the test bar may be due to the pre-heating cycle. The preheating time of one minute was picked arbitrarily. The pre-heating practice was later abandoned in favor of commencing the traverse when the coil was energized just beyond the edge of the block.

To determine the relative heatability of the materials, a point remote from the surface layer and the other irregularities mentioned above may be chosen and the temperatures compared. Choosing the point 0.100 inches from the surface and three inches from the left end, the temperatures for the various materials read: 4340 steel, 1087°F; 17-4 MO, 921°F; 17-7 PH, 964°F; and Thermold J, 1179°F. If 4340 steel is considered as 100% induction heatable, then induction heatability ratings can be given as: 17-4 MO, 84.8%; 17-7 PH, 88.6%; and Thermold J, 108.2%.

Heatability of Refractory Metals

Prior to determining the machinability of the refractory metals, studies were instituted to determine the heatability of these materials by radio-frequency techniques such as induction and resistance heating.

The results show that heating methods which depend upon relatively high permeability of the workpiece will have little success in elevating the temperature of refractory metals. While β-titanium was heated to 1200°F, the refractory metals tungsten, tantalum and molybdenum would not be heated above 450°F by induction.

Radio-frequency resistance heating was also tried with similar results. All of these materials have low permeability, and permeability determines the concentration of current. Radio-frequency current follows the path of least impedance which is the path which includes the least permeable material. When the material has a low permeability this preferred path is not as well defined and consequently the current and heat is not as concentrated.

An attempt was made to supplement induction heating by flame heating. A six tip oxygen-propane flame head was placed at exit from the induction coil in the face milling set-up. The increase in workpiece temperature was negligible and excessive oxidation occurred.

Figure 116 shows the relative induction heatabilities of the refractory materials and the other materials used. AISI 4340 is considered 100% as the base for these relations. R.F. resistance heatability ratings are within one or two percent of those given for induction heating.

Furnace heating was used for the preliminary tests on the refractory materials, but the problems of maintaining temperature, distortion due to uneven cooling, and the severe surface oxidation caused by exposure of the hot workpiece to air made this method impractical.

All tool life testing on the refractories was conducted in an inert argon atmosphere. This set-up is described under the inert arc heating section.

Temperature vs. Plate Power

The eighteen-thermocouple test block made of 4340 steel was used to determine the temperature vs. plate power relationships. The block was fed under the coil at a rate of 4-1/2 inches per minute while heat was applied across a 1/8'' gap at Inductron settings of L-1, L-2, L-3, L-4, H-1, and H-2 to give plate powers of 16, 18, 19, 24, 27, and 32 KW respectively. Temperatures were read and recorded against time, and temperature versus time graphs were constructed. Figure 117 depicts the time-temperature relationship for three thermocouples, i.e. Nos. 13, 7, 1 (located, as seen in Figure 109, 1/32'' beneath the surface and 1-1/2 inches, 4-1/4 inches, and 7 inches from the front of the block), when the test piece was heated with a plate power of 18 KW. Eighteen of these curves were constructed for each plate power input.

The maximum temperatures attained at 1/32, 1/8, and 5/16 inches from the surface were plotted in Figure 118. These curves are hyperbolic (of the form $TP^n = C$ where T = maximum temperature in F°, P = plate power in KW, and n and C are constants) due to the change in permeability with temperature. The surface, where the whole heat input takes place, is heated above the Curie point so that additional impressed power does not raise the temperature much. The flux density saturated the block for all power inputs so no change in permeability was caused by changing flux density. The equations for the various curves are:

$$\text{at } 1/32'' \text{ depth} - \text{Temp.}_{\text{max.}} = 890\ P^{0.105}$$

$$\text{at } 1/8'' \text{ depth} - \text{Temp.}_{\text{max.}} = 784\ P^{0.113}$$

$$\text{at } 5/16'' \text{ depth} - \text{Temp.}_{\text{max.}} = 514\ P^{0.206}$$

These formulae may be reduced to:

$$\text{Temp.}_{\text{max.}} = 76 + 877e^{-2.13d} \times P^{1.375d^2 - 0.112d + 0.1071}$$

where d = depth below heated surface.

The temperature at a time after the maximum temperature is reached may be determined by averaging the cooling curves at the various thermocouples. This is necessary to determine the temperature under the tool, i.e., the cutting temperature as opposed to the maximum temperature or the tempering temperature. The temperature may be determined by the empirical formula.

$$\text{Temp}_t = \text{Temp.}_{\text{max.}} \times e^{-(17.25\ \text{depth}^2 - 5.74\ \text{depth} + 0.43)t}$$

where t is the time elapsed since maximum temperature in seconds.

The maximum temperature occurred under the end of the coil. The above formulae are only valid under the limits of 5/16" depth, 32 KW plate power, and 60 seconds cooling time.

<u>Temperature vs. Feed Rate</u>

The AISI 4340 steel test block with eighteen embedded thermocouples was used to determine the temperature-feed relationships. Tests were made with a power input of 19 KW at table feed rates of 1-7/7, 2-1/4, 2-5/8, 3-1/4, and 4-1/2 inches per minute. The test procedure was the same as for the temperature versus plate power relationship. Figure 119 is representative of the 90 time-temperature relations obtained. They show the effect of feed on the temperature of one point, namely, 1/32 inch beneath the surface, 4-1/4 inches from the front of the block.

Figure 120 shows a plot of the maximum temperatures attained, 1/32, 1/8, and 5/16 inches beneath the surface with various feed rates. The variance of the points renders an exact formula useless, but it is interesting to note that the temperature increases with a decrease in feed, and that the rate of this temperature increase is higher at a greater distance from the surface. This is due to the fact that the surface layers are approaching equilibrium, when the heat loss in BTU/sec. approaches the heat input. This is not true for greater depths where a longer time for heat transfer allows more heat to build up with consequent higher temperature.

Temperature vs. Coil Gap

The air gap between the induction coil and the workpiece is important. If the gap is too small, the workpiece may expand until it shorts out the coil, or a chip might become wedged between the coil and work and short out the coil. If the gap is too large, the coupling between coil and work decreases, efficiency suffers and a lower temperature is obtained.

Figure 121 shows the relation between coil gap and the temperature of a thermocouple 1/32 inch beneath the work surface directly under the center of the coil after 30 seconds heating. Figure 122 shows the effect of coil gap on the surface temperature for four materials. The temperature measurements were made with a contact pyrometer. As has been stated, a coil gap of 1/8 inch has been standard during these tests.

Temperature vs. Position under Coil

It is known that a pancake coil transfers more energy near the center than near the ends. The distribution of energy transfer is important, particularly to the design of coils for lathe work. Figure 123 shows the temperature 1/32 inch below the work surface for various positions along the coil face. It may be seen that the center portion of the coil produces far more heat than the ends. This information is used in the design of induction coils for lathe work. The coil is bent to a radius equal to one-half the largest diameter plus 1/8 inch (the coil gap), and as the diameter is reduced, the coil is moved in to maintain the 1/8 inch gap in the center of the coil. The ends will have a larger gap but since little of the energy is transferred at this point, the loss is not great.

Radio-Frequency Resistance Heating

Tests were run on the 4340 test block with eighteen embedded thermocouples. Figure 124 shows the time-temperature relation. The steepness of the curve should be noted. The temperature rises very sharply and fails almost as rapidly. This is both an advantage and disadvantage. Time is necessary for tempering or other metallurgical effects; therefore, these effects are held to a minimum with the sharp temperature peak. The sharp peak makes the placement of the tool critical. If it is not placed correctly, it will cut relatively cold metal. The maximum temperatures reached are not as high as the temperatures under corresponding conditions with induction heating. Insufficient data is presently available to determine temperature-plate power-feed rate relationships.

FIVE THERMOCOUPLE - TEST BLOCK USED FOR DETERMINING INDUCTION HEATABILITY OF METALS

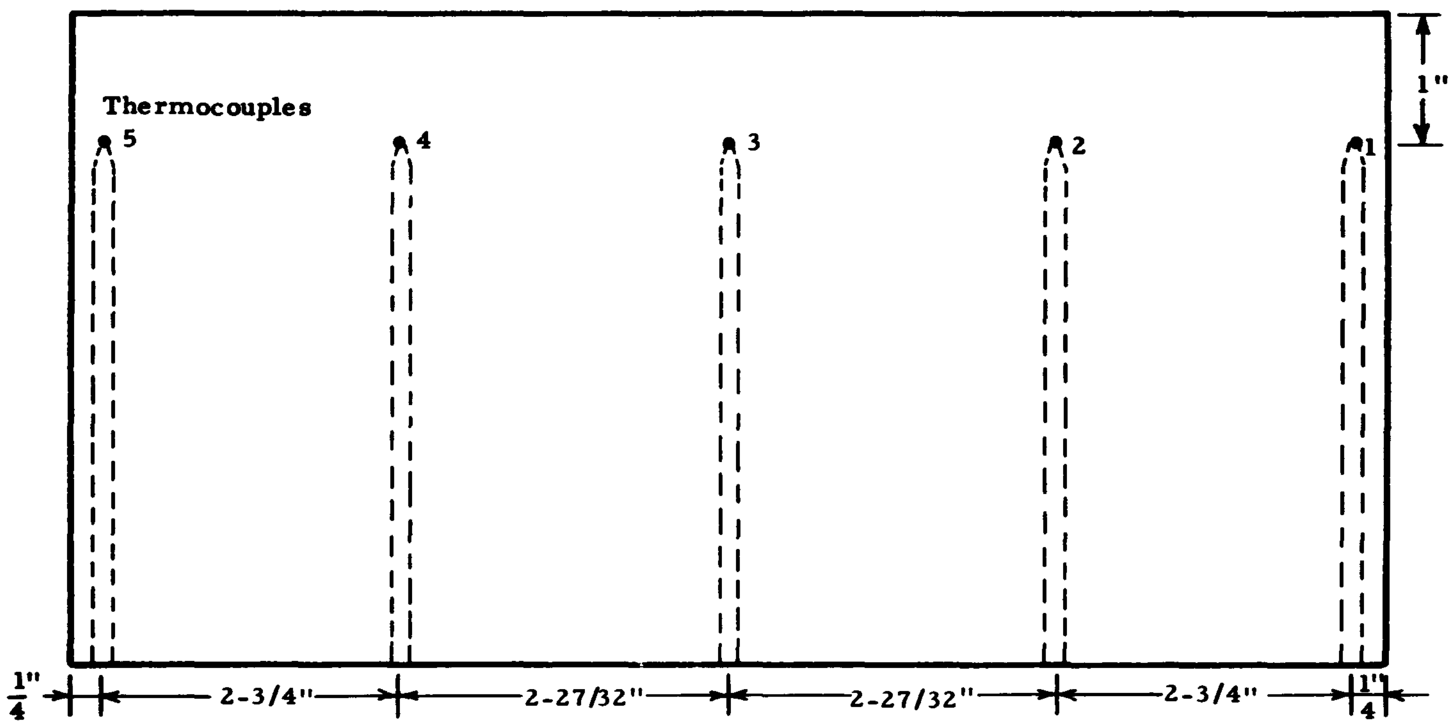


FIGURE 108

EIGHTEEN THERMOCOUPLE - TEST BLOCK OF AISI 4340 STEEL USED FOR DETERMINING HEAT FLOW AND DISTRIBUTION

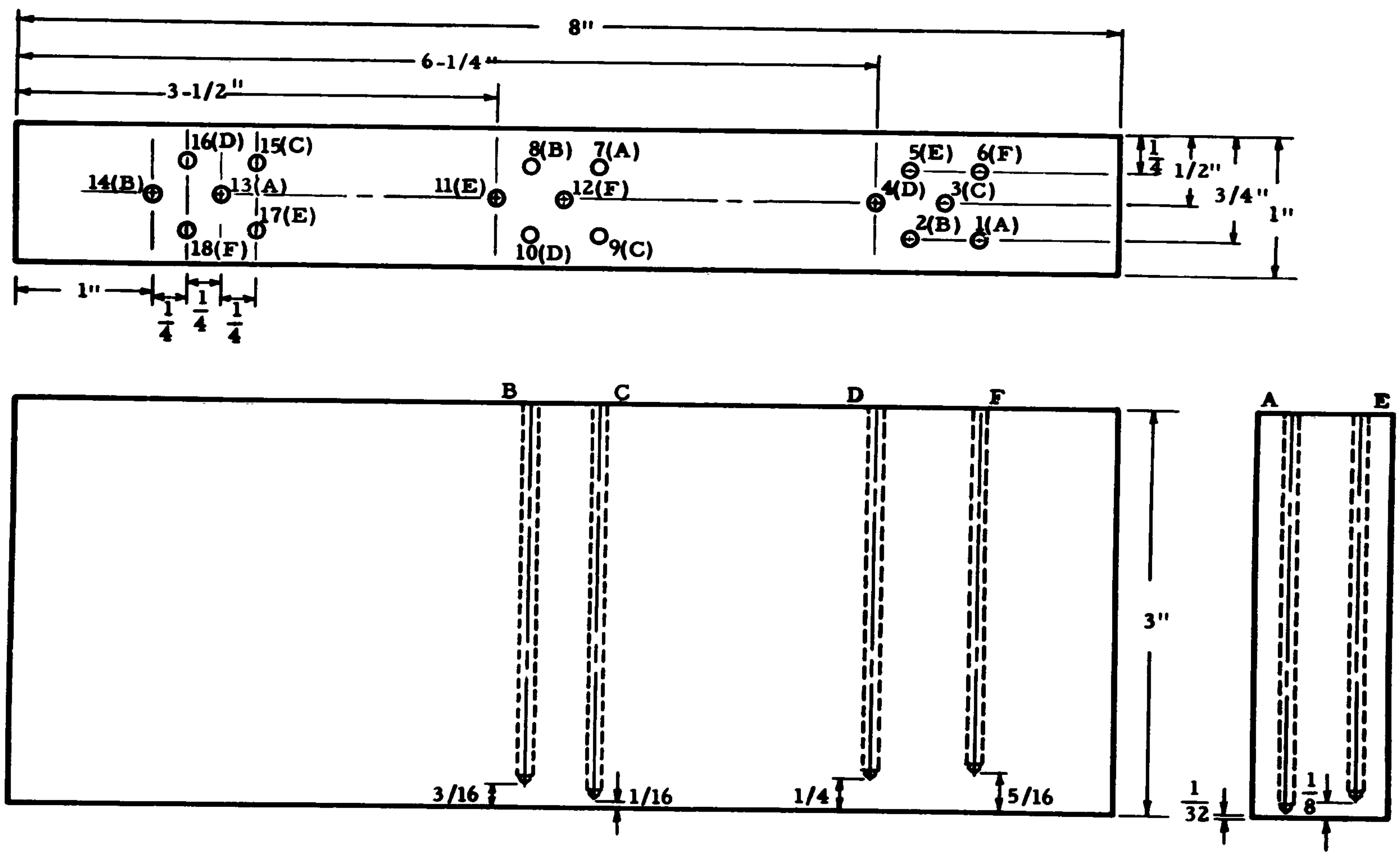


FIGURE 109

WORKPIECE TEMPERATURE DISTRIBUTION MEASURING APPARATUS
Heating Coil, Eighteen-Thermocouple Test Block, Thermocouple Selector Switch, Recorder, and Amplifier

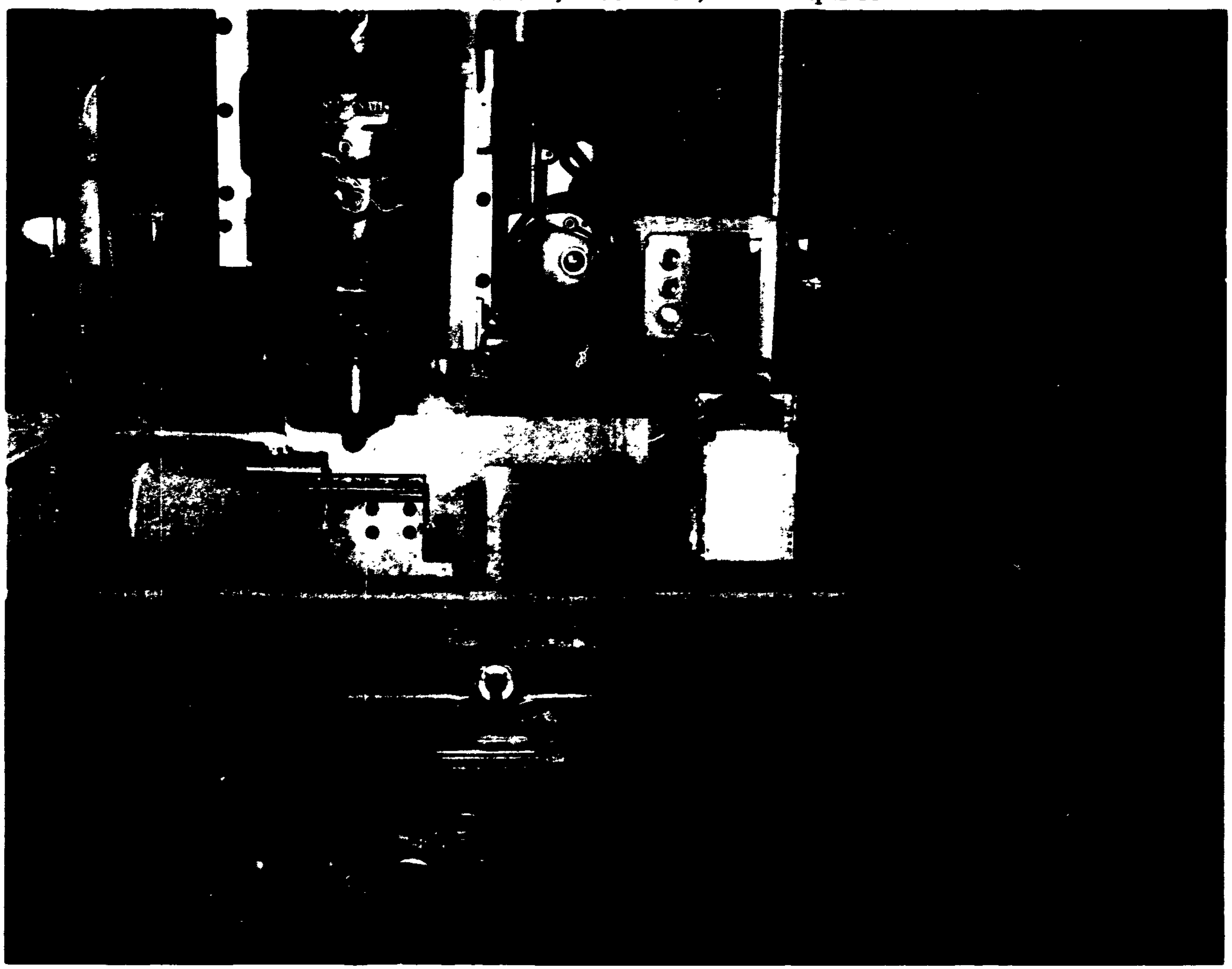


FIGURE 110

WORKPIECE TEMPERATURE DISTRIBUTION MEASURING APPARATUS

Selector Switch, Eighteen-Thermocouple Test Block, and Heating Coil

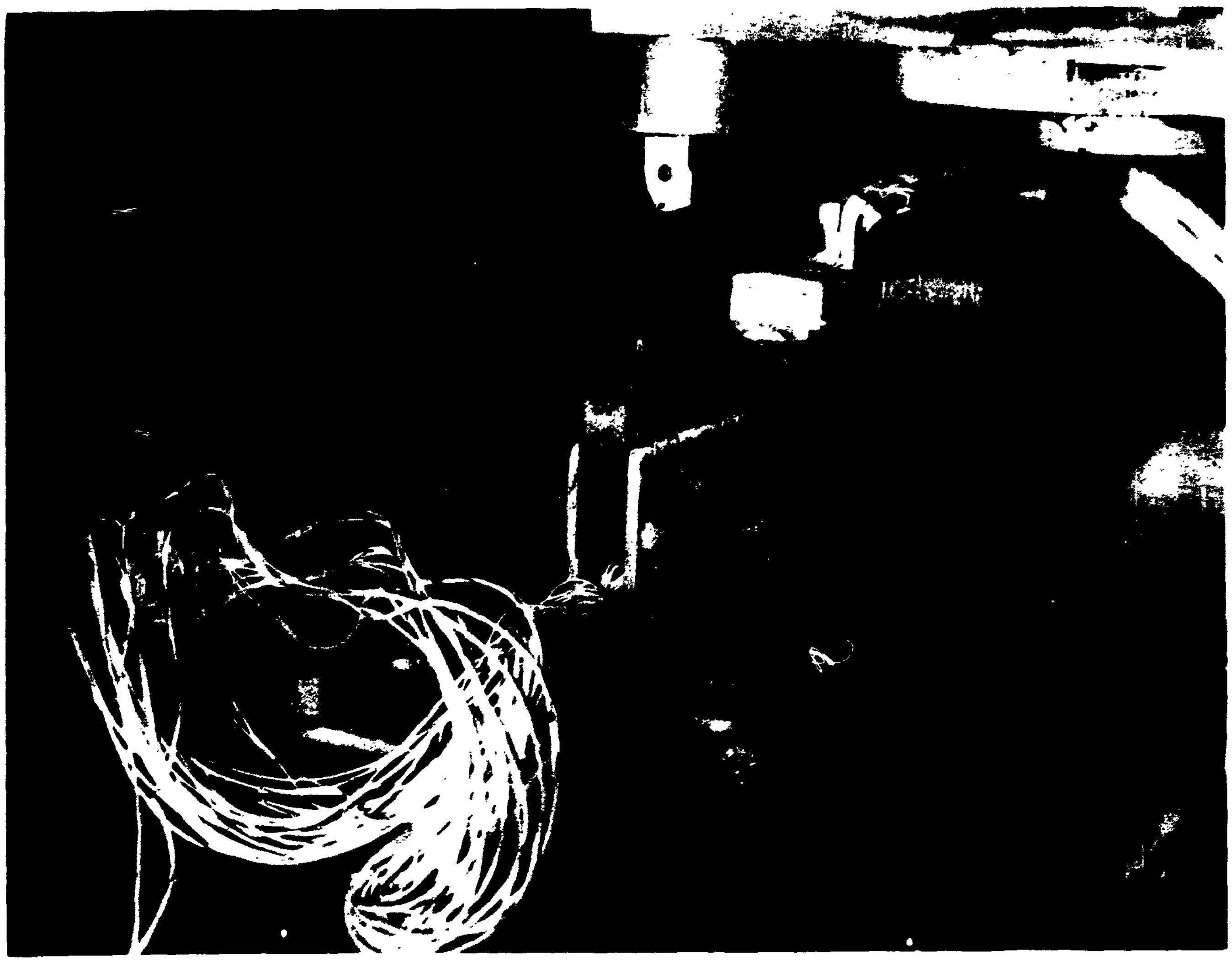
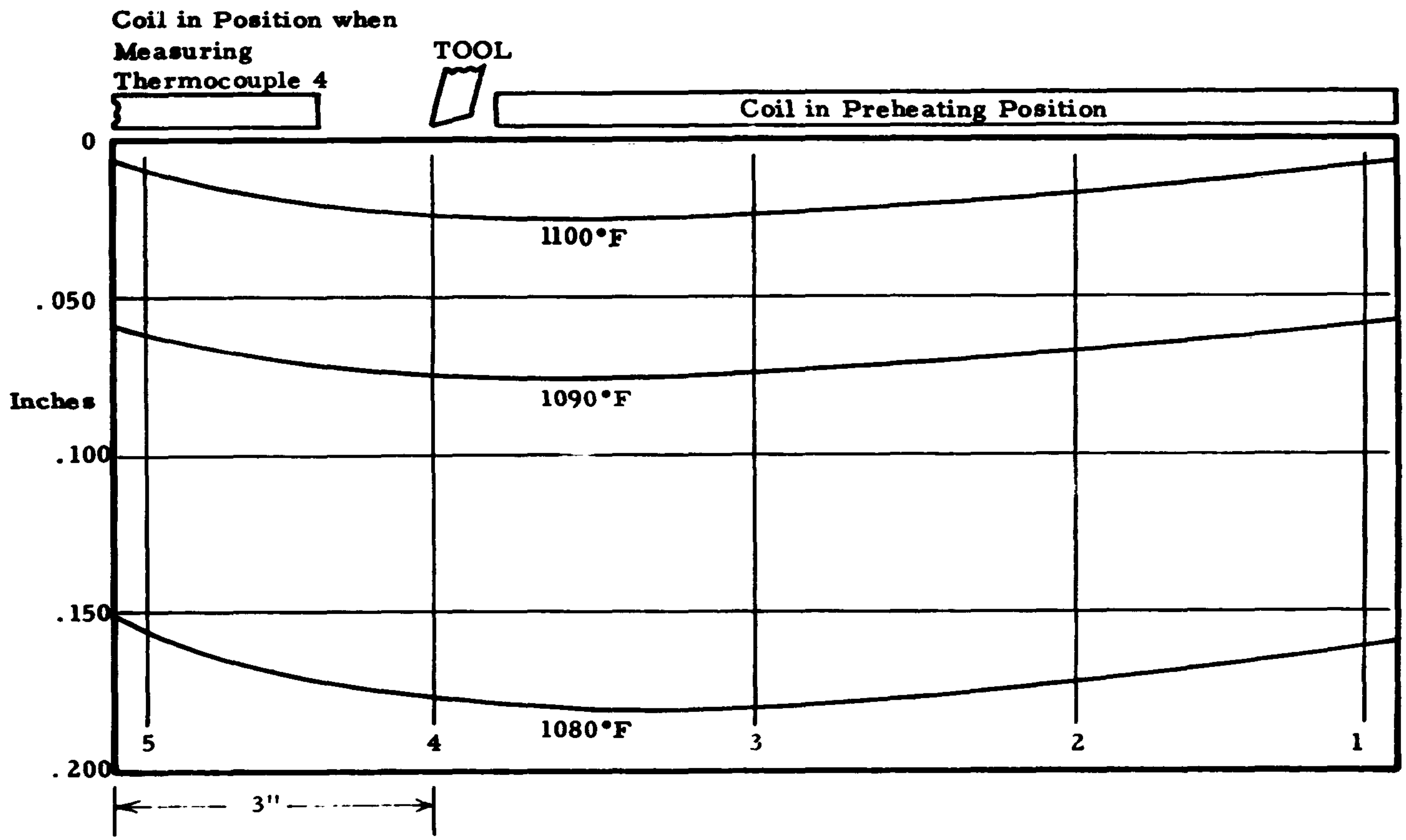


FIGURE 111

INDUCTION HEATABILITY OF AISI 4340
TEMPERATURE DISTRIBUTION AT DEPTHS BENEATH THE SURFACE
HEAT INPUT 27 KW TABLE FEED RATE 4-1/2 IN/MIN.



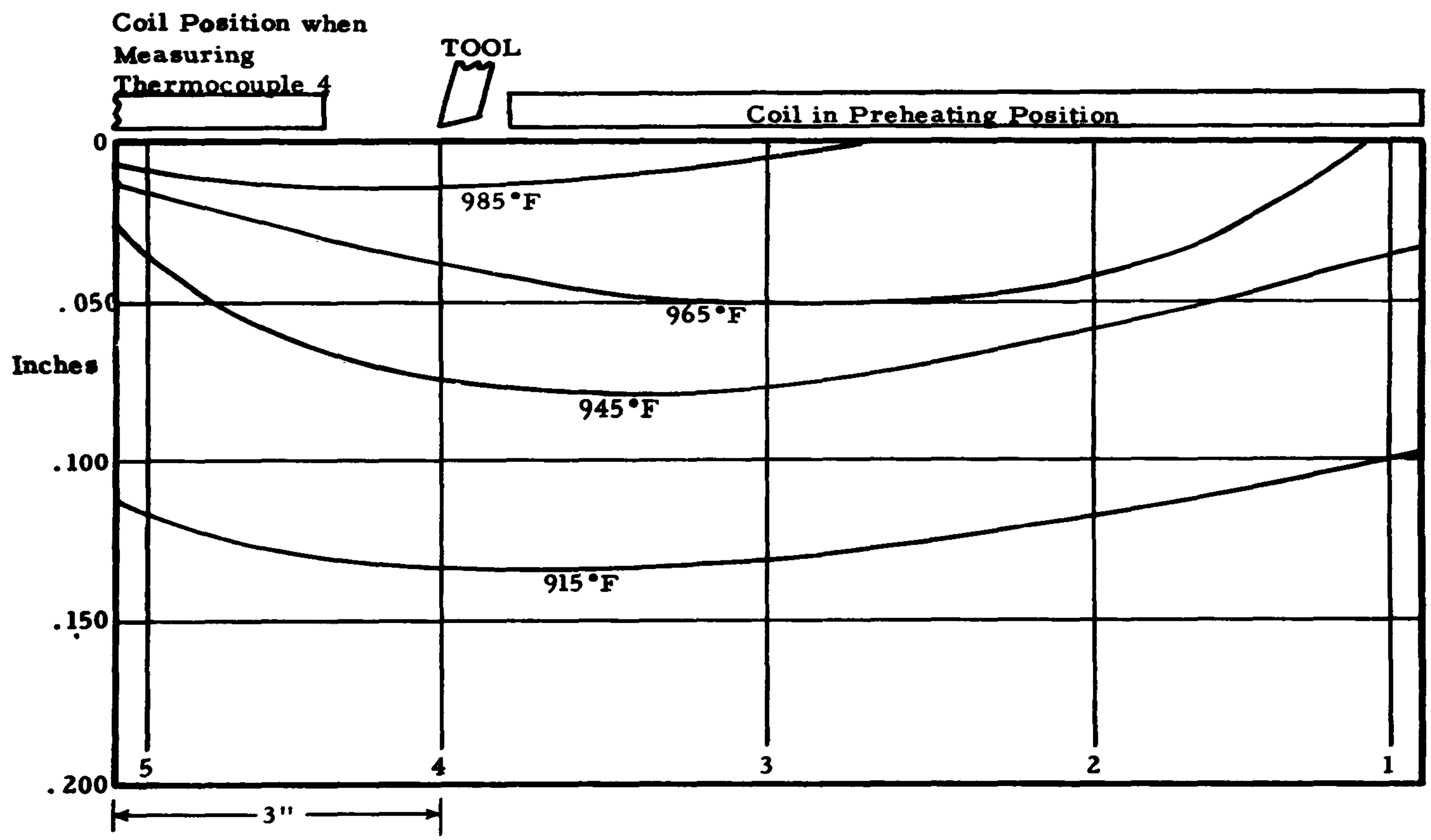
Thermocouple Number Refers to Figure 54

FIGURE 112

INDUCTION HEATABILITY OF 17-4 MO

TEMPERATURE DISTRIBUTION AT DEPTHS BENEATH THE SURFACE

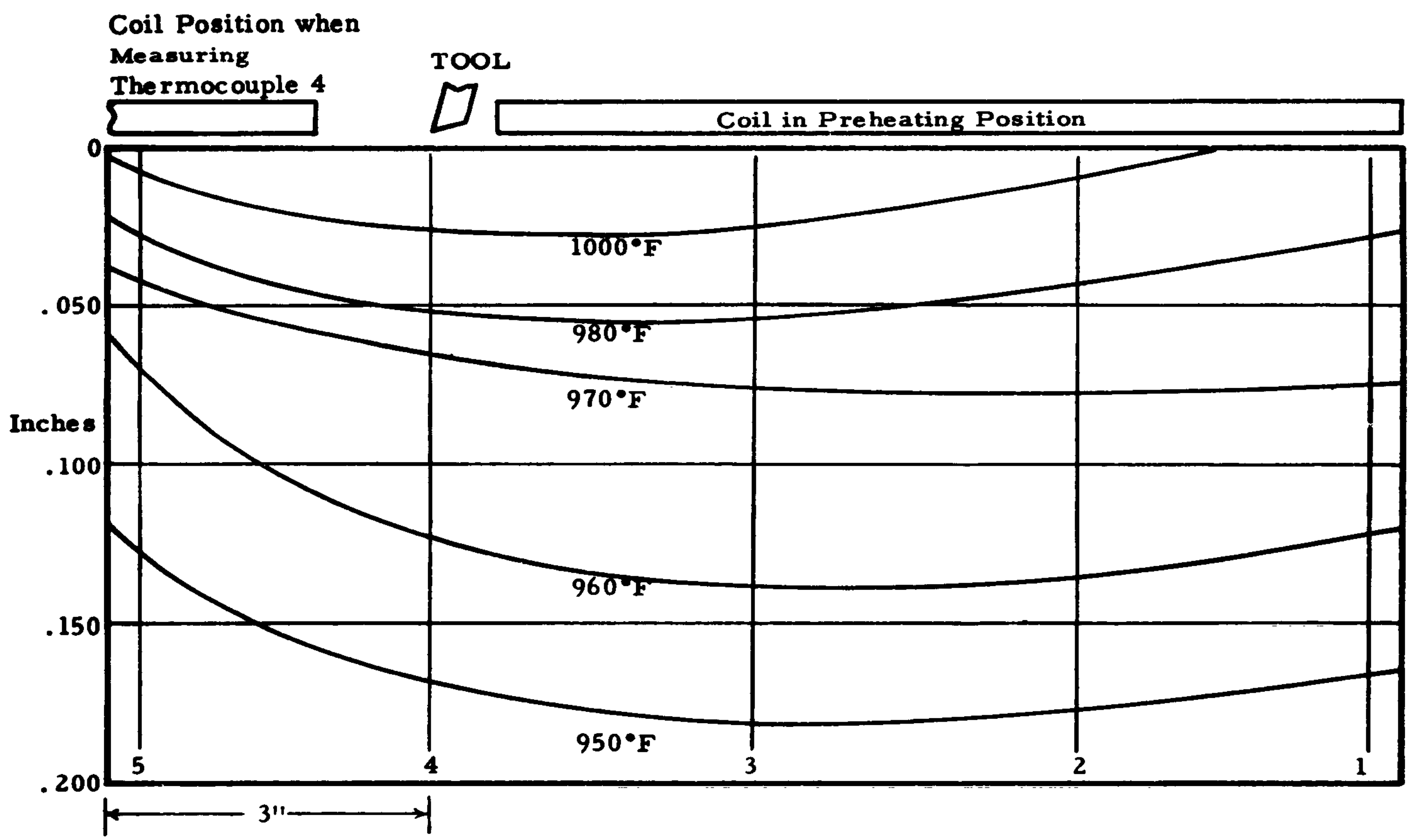
HEAT INPUT 27 KW TABLE FEED RATE 4-1/2 IN/MIN.



Thermocouple Number Refers to Figure 54

FIGURE 113

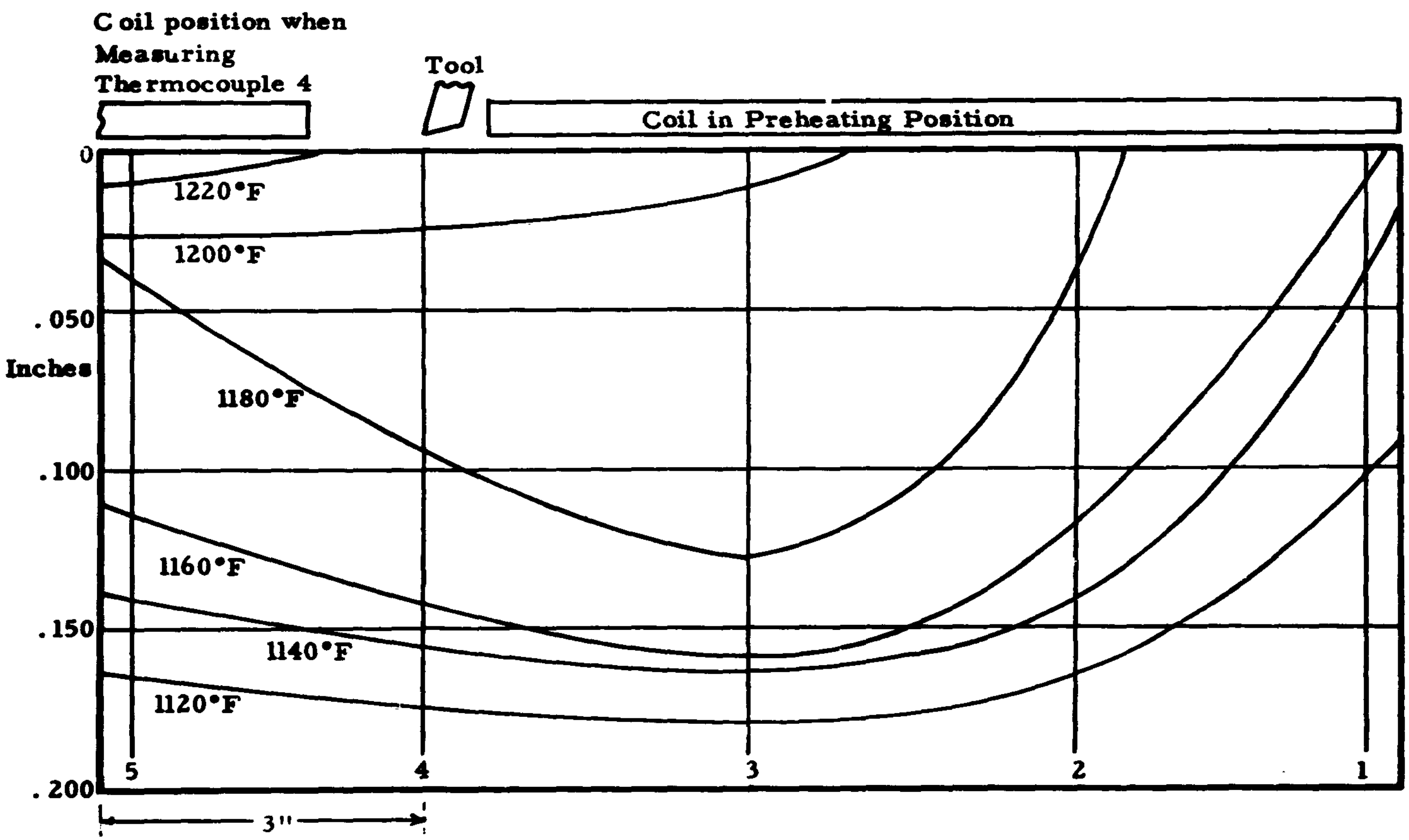
INDUCTION HEATABILITY OF 17-7 PH
TEMPERATURE DISTRIBUTION AT DEPTHS BENEATH THE SURFACE
HEAT INPUT 27 KW TABLE FEED RATE 4-1/2 IN/MIN.



Thermocouple Number Refers to Figure 54

FIGURE 114

INDUCTION HEATABILITY OF THERMOLD J
TEMPERATURE DISTRIBUTION AT DEPTHS BENEATH THE SURFACE
HEAT INPUT 27 KW TABLE FEED RATE 4-1/2 IN/MIN.



Thermocouple Number Refers to Figure 54

FIGURE 115

RELATIVE INDUCTION HEATABILITIES FOR VARIOUS MATERIALS

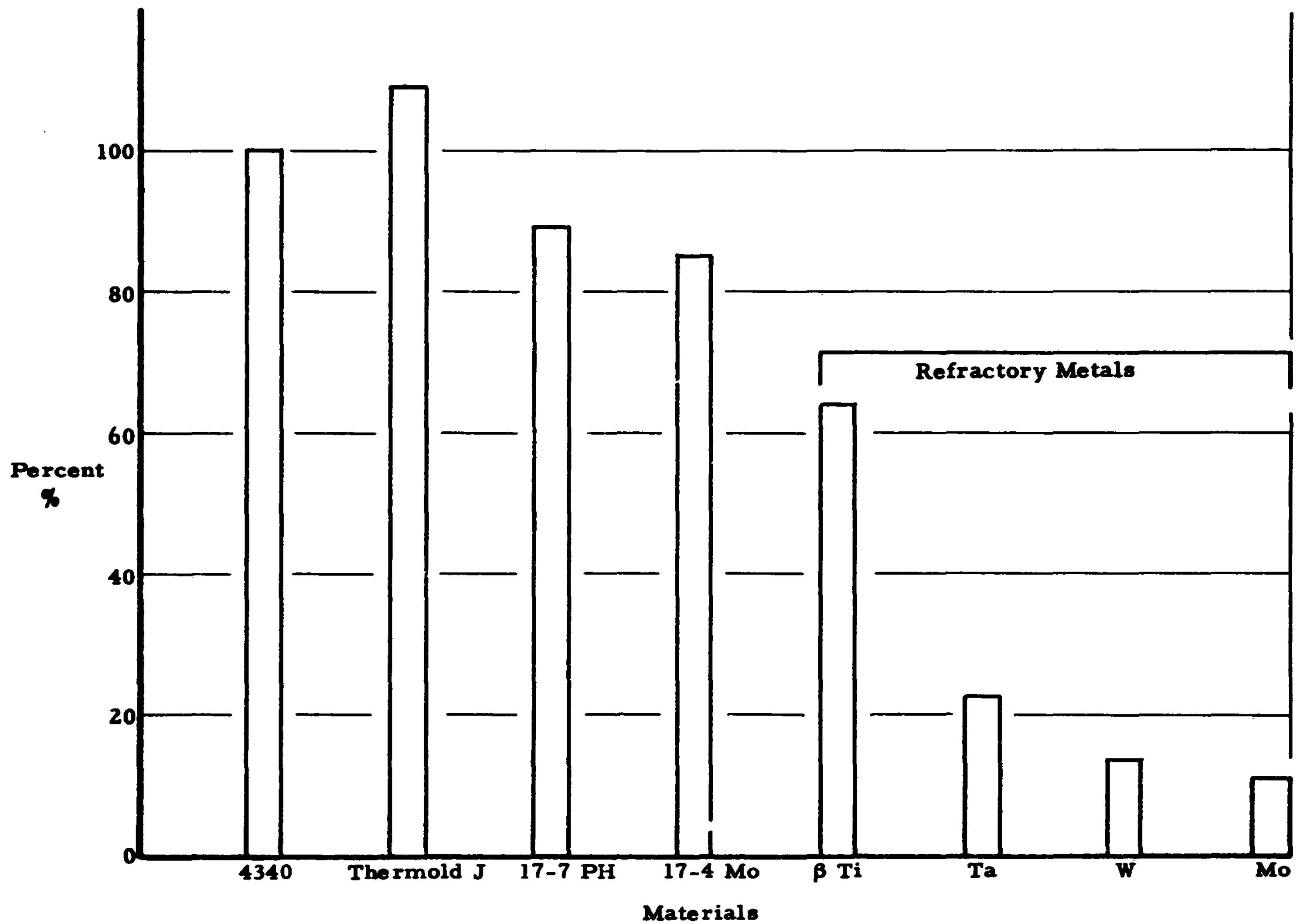


FIGURE 116

TIME-TEMPERATURE RELATIONSHIP FOR AISI 4340
HEAT INPUT 18 KW TABLE FEED RATE 4-1/2 IN/MIN.
1/32 INCH BENEATH THE SURFACE

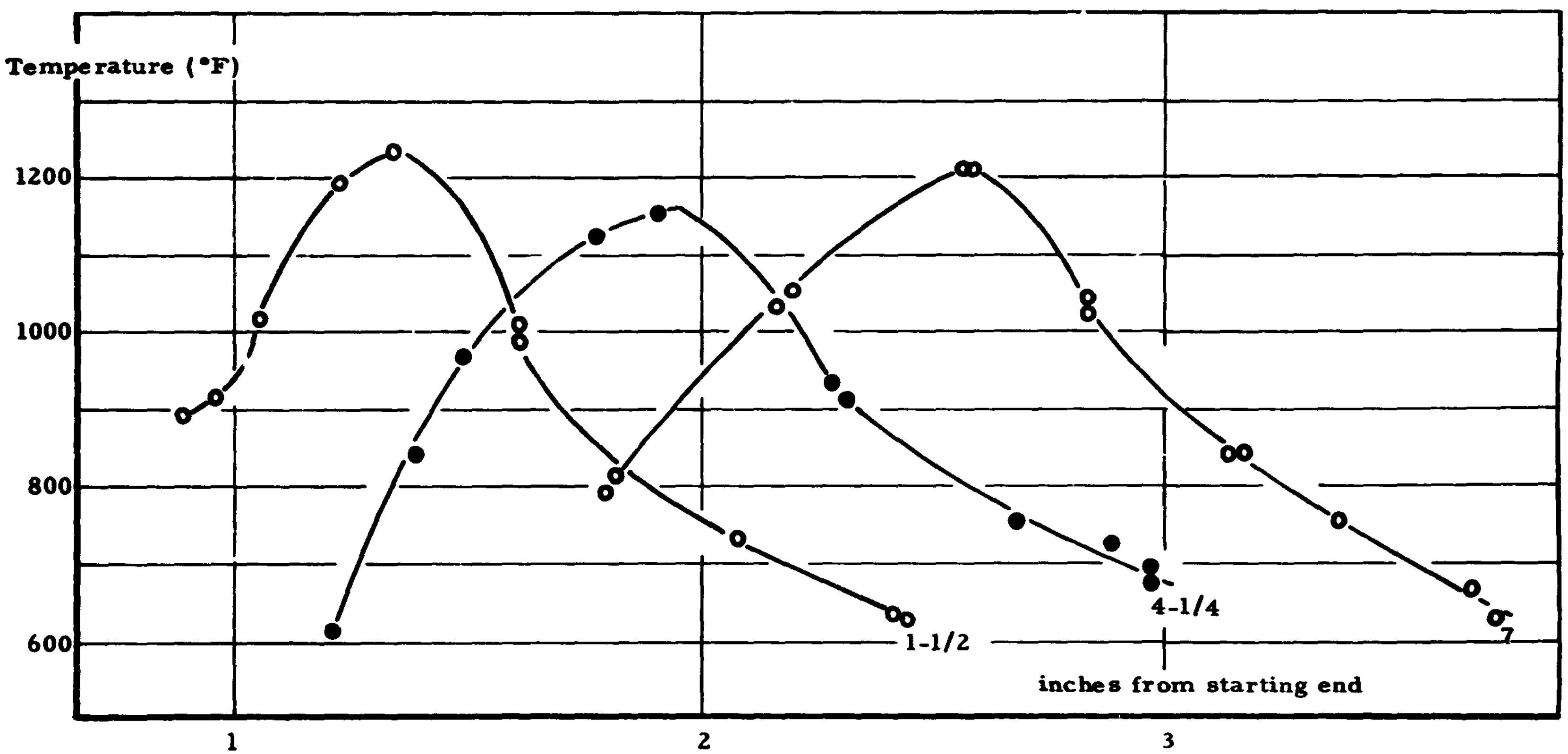


FIGURE 117

EFFECT OF PLATE POWER INPUT ON TEMPERATURE AT VARIOUS DEPTHS - TABLE FEED RATE 4-1/2 INS PER MIN.

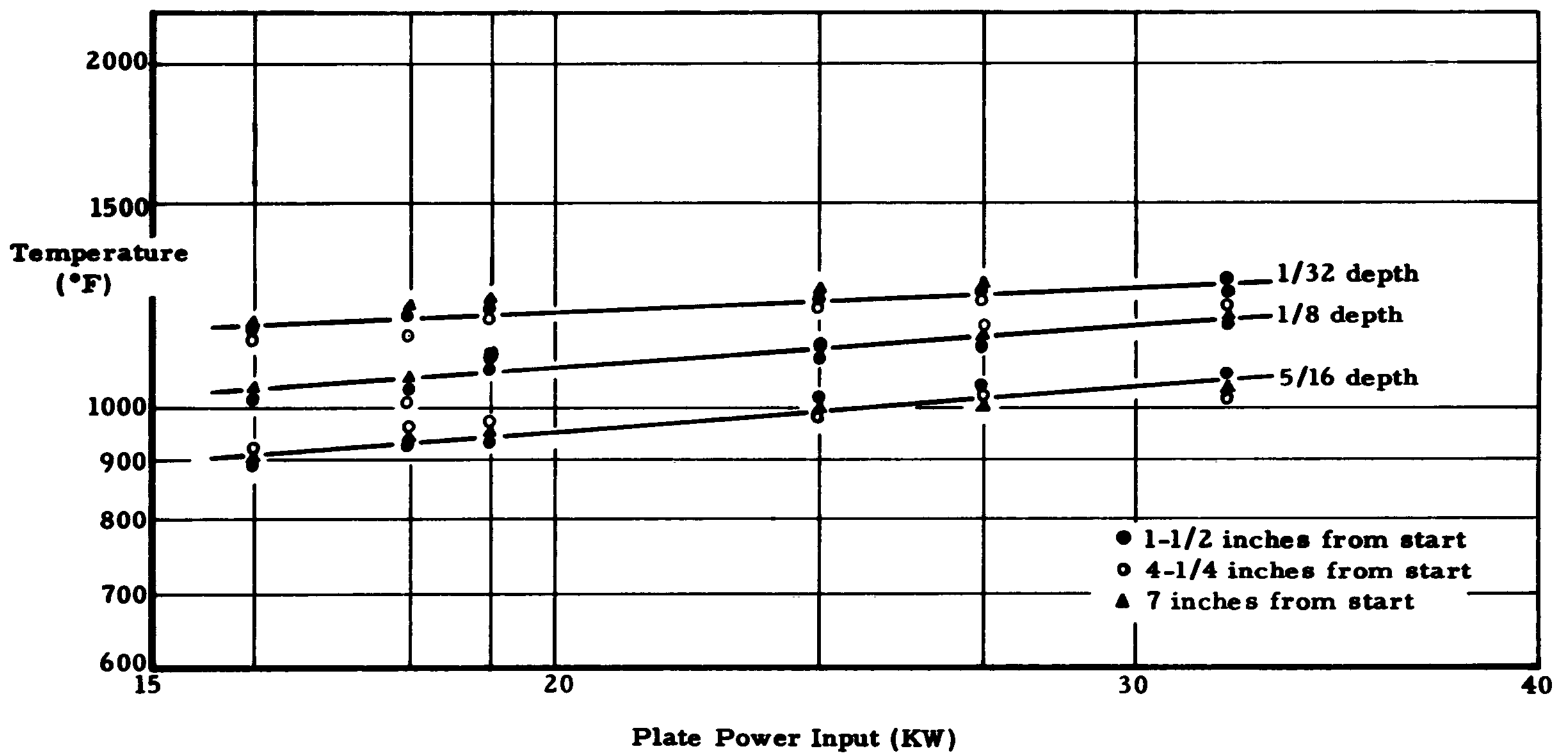
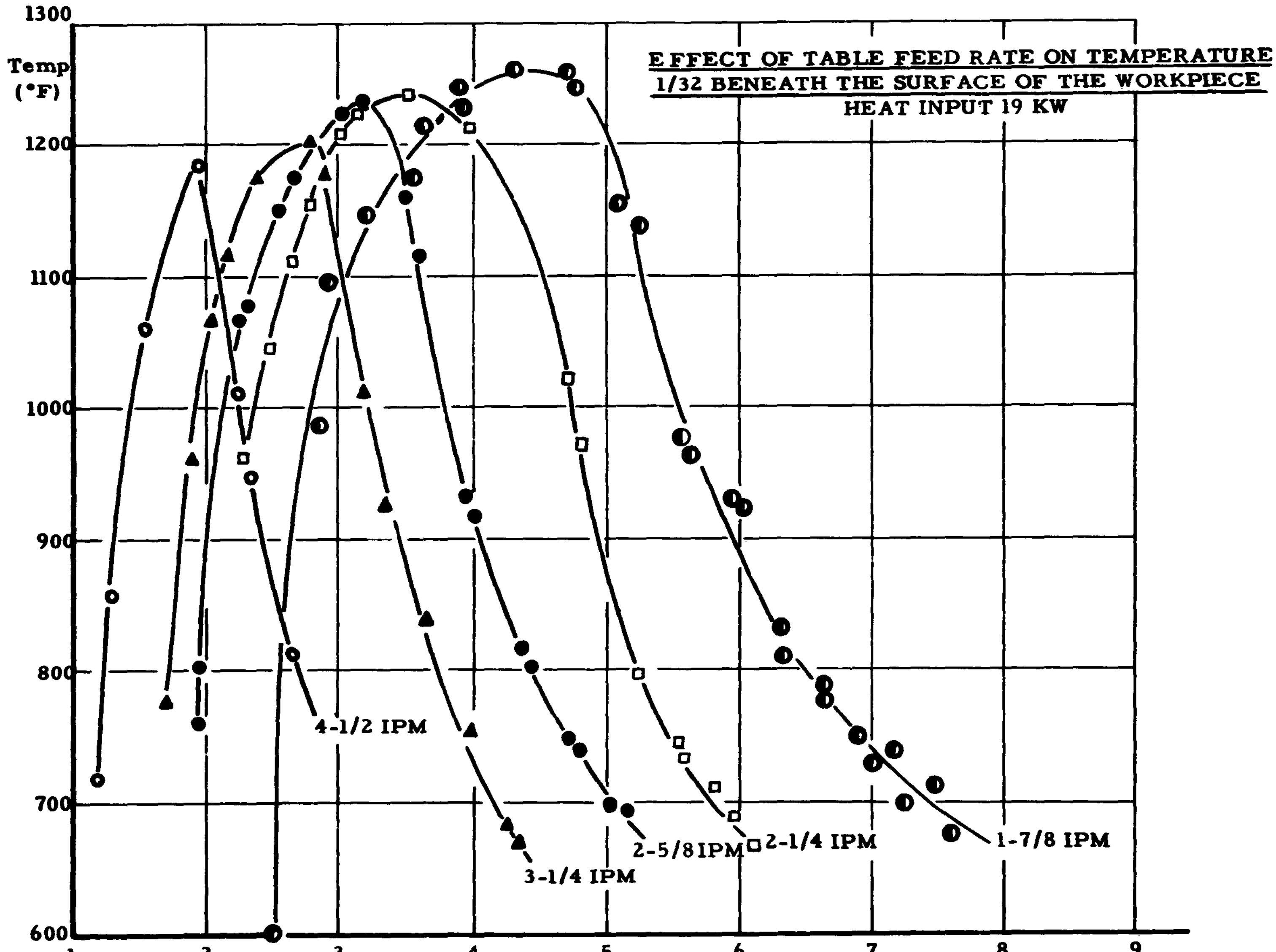


FIGURE 118



EFFECT OF TABLE FEED RATE ON TEMPERATURE
1/32 BENEATH THE SURFACE OF THE WORKPIECE
HEAT INPUT 19 KW
Temp
(°F)
1300
1200
1100
1000
900
800
700
600
1
2
3
4
5
6
7
8
9
(Min)
4-1/2 IPM
3-1/4 IPM
2-5/8 IPM
2-1/4 IPM
1-7/8 IPM

FIGURE 119

EFFECT OF FEED ON MAXIMUM TEMPERATURE AT VARIOUS DEPTHS - PLATE POWER INPUT 19 KW

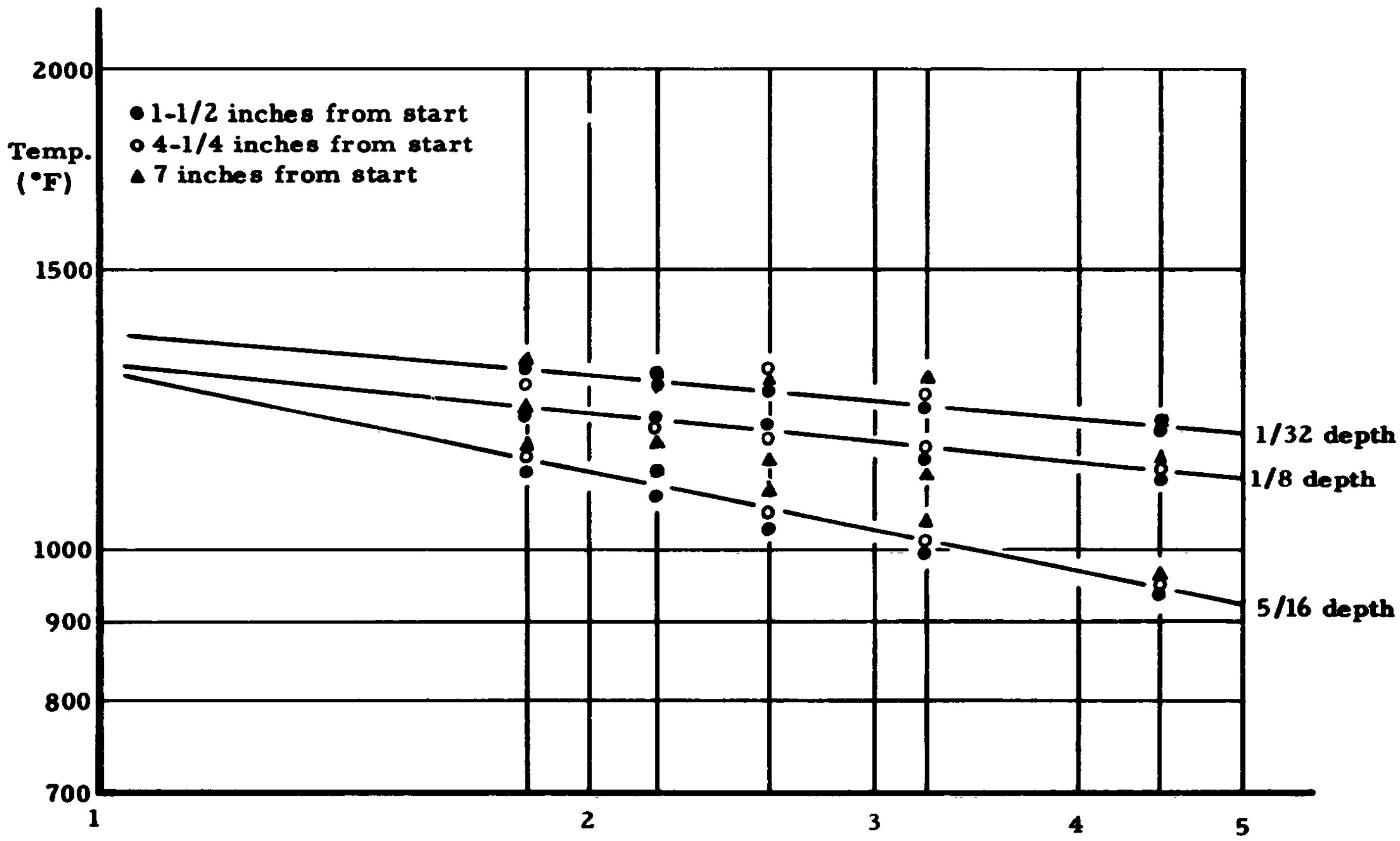


FIGURE 120

EFFECT OF COIL GAP ON TEMPERATURE
1/32 BENEATH THE SURFACE OF AISI 4340
POWER INPUT 19 KW, NO FEED, HEATING TIME 30 SECONDS

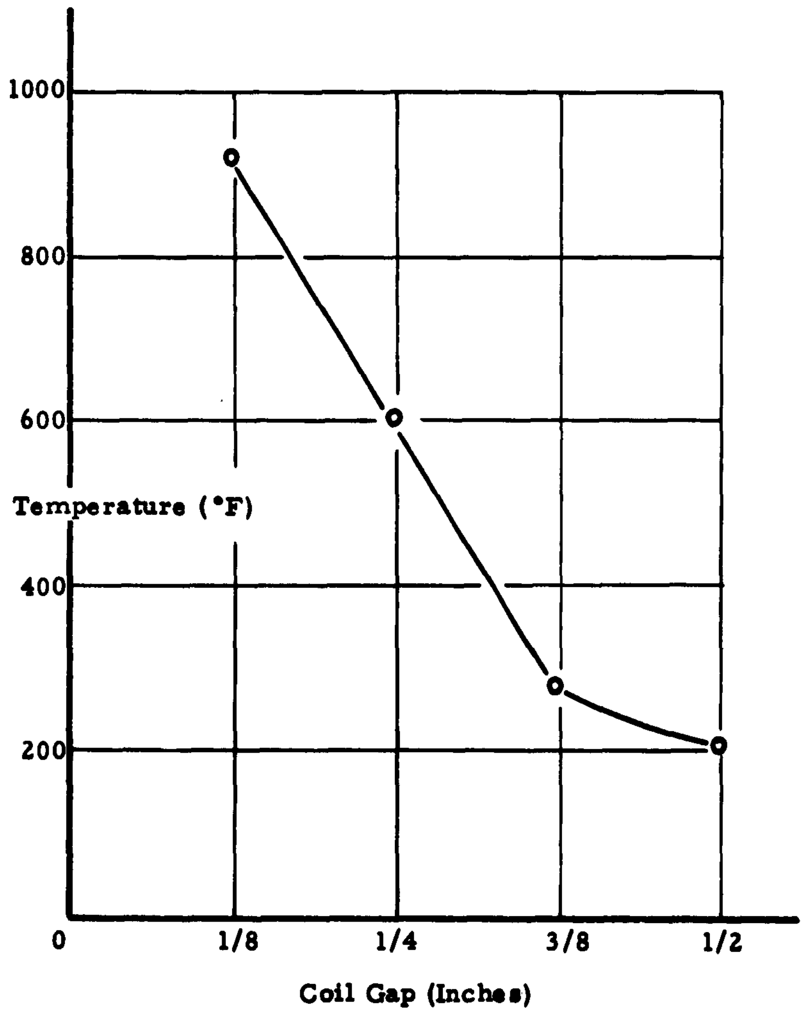


FIGURE 121

EFFECT OF COIL GAP ON SURFACE TEMPERATURE
WITH VARIOUS MATERIALS
PLATE POWER INPUT 27 KW TABLE FEED RATE 4-1/2 IN/MIN.

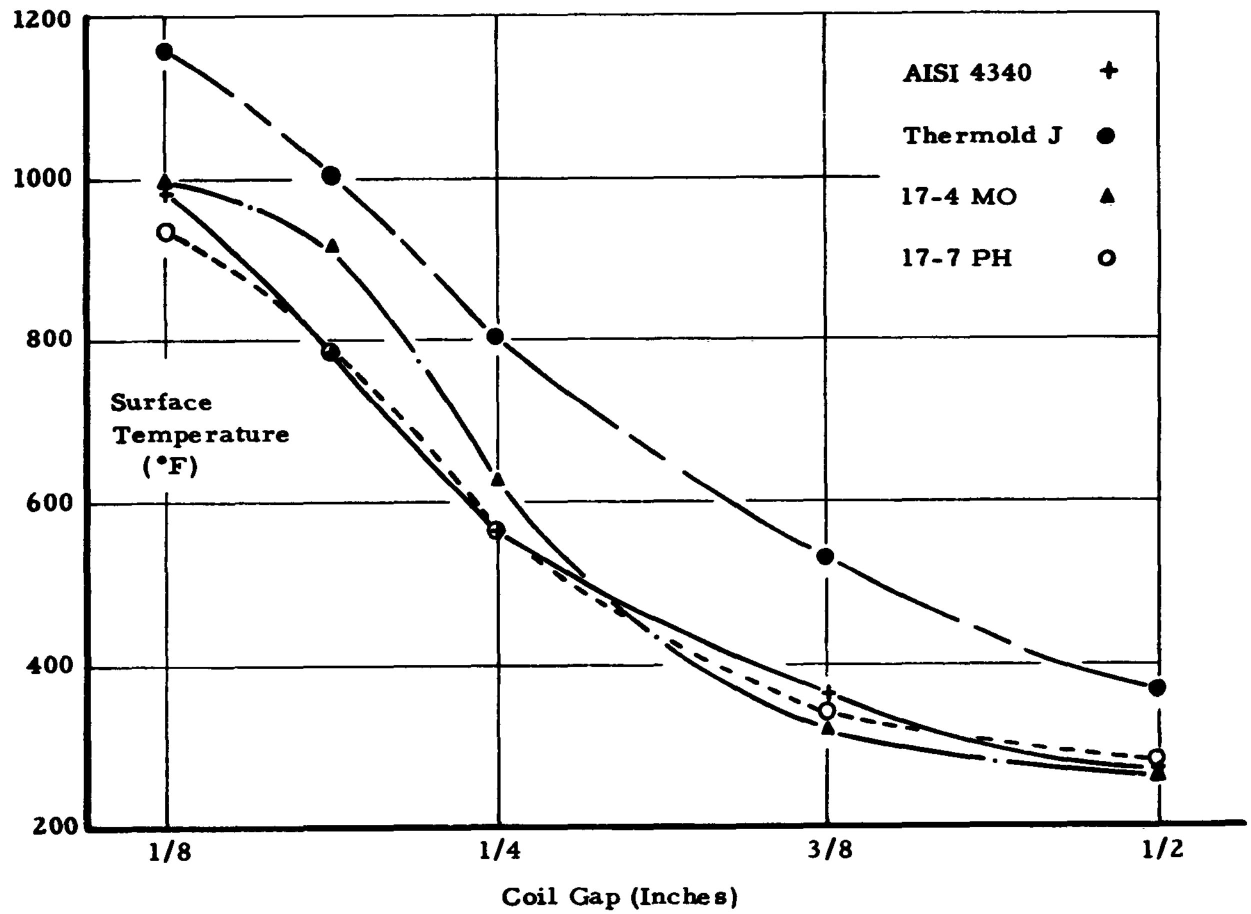


FIGURE 122

EFFECT OF POSITION UNDER THE COIL ON TEMPERATURE
PLATE POWER INPUT 19 KW, NO FEED, HEATING TIME 30 SECONDS

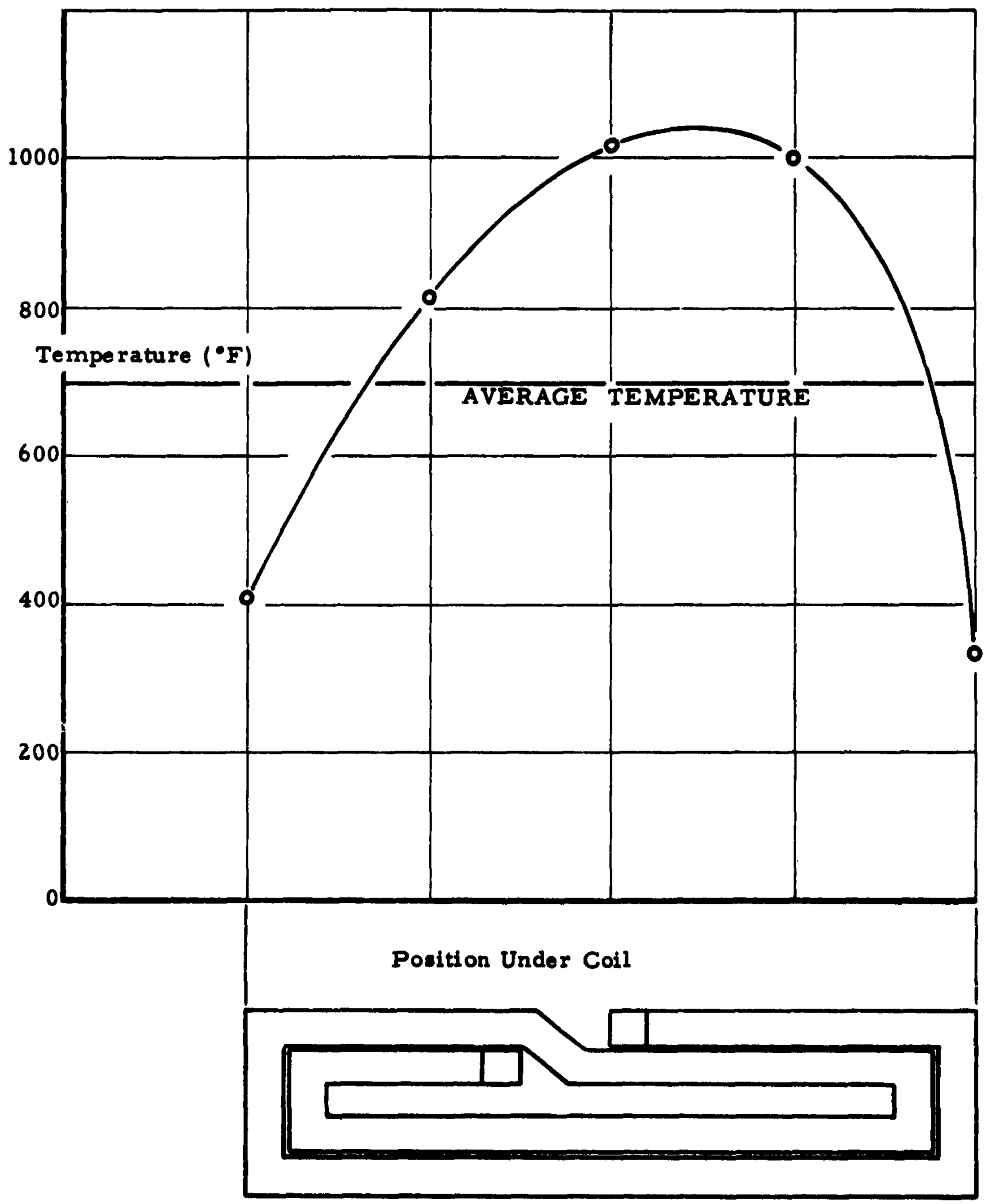


FIGURE 123

TIME-TEMPERATURE RELATIONSHIP
RADIO FREQUENCY RESISTANCE HEATING

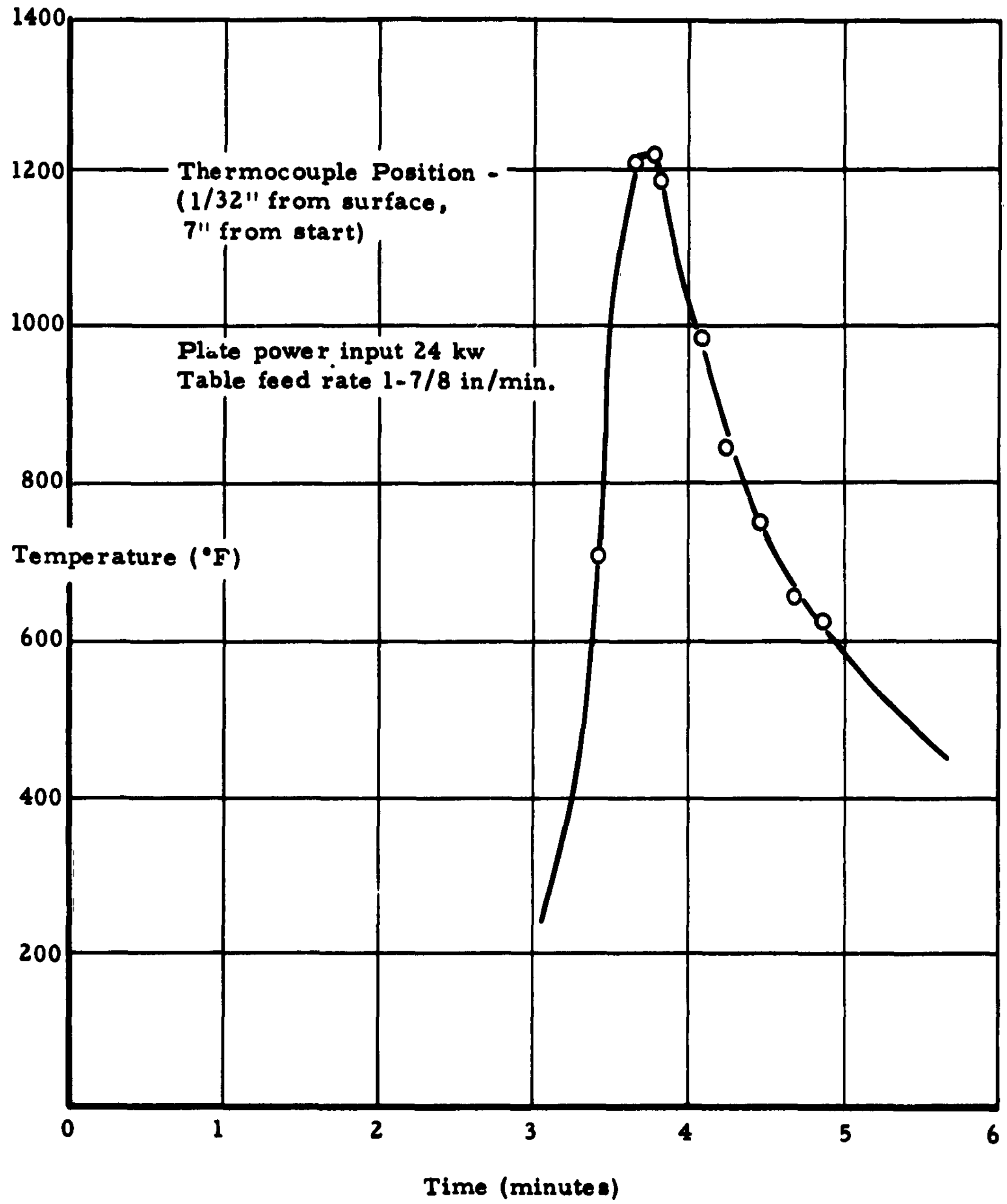


FIGURE 124

SAFETY AND HEALTH HAZARDS

Hot machining is not dangerous but does present more hazards than conventional production machining.

Some of the additional hazards are as follows:

(1) The workpiece and perhaps the fixture is heated. Asbestos gloves are necessary for loading and unloading the workpiece. A protected place for cooling the workpiece is required so that personnel do not inadvertently touch the hot workpiece. The constant glow from the hot work could possibly affect the worker's eyes. Tinted safety glasses may be required.

(2) While the chips are normally not much hotter than in ordinary production, higher production rates increase their number. Protective guards are necessary to control the flying chips. Transparent plastic is recommended to allow a clear view of the operation.

(3) The operator must be protected from the heating apparatus. When flame heating is used, guards must be such that the operator cannot ignite his clothes. When d.c. or ordinary a.c. electricity is used, only low voltages should be applied or care taken to prevent the possibility of electrocution. Higher voltages may be tolerated for radio-frequency current because this current flows over rather than through a person due to "skin effect". Burns are possible but not electrocution. This should be explained to the operator so he respects but does not fear the equipment.

(4) Exhaust blowers may be necessary if vaporous or toxic friction reducing agents are used or if the workpiece is coated with oil. If several machines use hot machining in one area, blowers will help maintain a satisfactory working temperature.

(5) The machine tool should also be protected. Asbestos sheeting can be used to interrupt all paths of conduction to the machine. If any part of the machine is heated excessively, the oil temperature in that part should be checked and, if necessary, a larger sump or an oil cooler

should be provided. If table or ways are heated, coolant should be played over them, ensuring, however, that none gets on the heated workpiece. It is extremely important that no coolant be allowed to splash on an induction coil or the coil will short-circuit and may be burned out.

REFRACTORY SECTION

Introduction

As the pace of technological progress quickens, a host of new metals and alloys are becoming commercially available. However, many of these new alloys defy conventional methods of machining, and industry is required to modify present means of fabrication to use these metals advantageously.

This investigation was undertaken to evaluate elevated temperature techniques in machining these alloys. While actual part configurations may vary, basic knowledge derived from this study will aid in forming a sound approach to successfully machining these materials.

Certainly, prominent on the list of high strength, thermal resistant alloys are refractory metals. The term "refractory" refers to metals having a melting point higher than 2000°C (3632°F), and includes tungsten, molybdenum, tantalum, columbium, boron, hafnium, ruthenium, osmium, rhenium, and iridium. Today's demand for useful, high temperature metals in electronics, aviation, missile, and related aerospace fields has resulted in an astonishing development of four of these elements -- tungsten, molybdenum, tantalum, columbium, and their alloys. These four metals possess unusual mechanical, physical, and chemical properties, and are available most readily, fabricated most easily, and are, therefore, in more demand than the other six refractory metals.

The increased use of these refractory metals and alloys by the aerospace industry was confirmed by an industrial survey of a considerable number of companies engaged in this type of work. But the paramount result educed from this survey is that refractory metals are not miracle metals! In fact, all four are relatively costly, lack elevated temperature corrosion and oxidation resistance, and most important -- yield extremely low productivity rates.

Low productivity rates prompted investigation into utilizing previously successful hot machining techniques to improve the machining characteristics of these alloys. The industrial survey indicated that the greatest fabrication difficulties were encountered with several titanium alloys in addition to the four refractory metals mentioned. The need for the supplementary hot machining evaluation of these metals was further enhanced by our previous preliminary work on a few refractory alloys.

A recent field survey made through visits to important aerospace companies just prior to commencing the supplementary research enabled the authors to appreciate the latest and most significant problems now experienced in machining these alloys.

Tungsten and molybdenum share general properties, which include difficulty in fabrication, low ductility at room temperature, low gas solubility, and strain rate sensitivity. Machining of these two metals usually results in workpiece chipping and spalling, with breakout of tungsten during interrupted curring a common problem. The lower cut speeds that are necessary and the extremely short tool lives experienced, make conventional machining very expensive.

Tantalum and columbium, on the other hand, may be cold worked, have low brittle-ductile transition temperatures, high gas solubility, and are relatively insensitive to strain rates. When machining, it is necessary to overcome seizing, galling, and tearing tendencies of these metals. Low tool lives are experienced due to a pronounced chip to tool "welding" tendency that both metals exhibit.

Titanium alloys also display the same welding tendency. Titanium possesses unique properties, such as low thermal conductivity and low specific heat. This contributes to high heat concentration at the tool-chip interface and a subsequent lowering of tool life.

REFRACTORY METALS - PRELIMINARY WORK

Supplementing the machining tests on various high strength alloys as reported on pp. 68-75, a limited preliminary study on refractory metals was made. These results encouraged the extension of our investigation of hot machining refractory metals as reported in this section.

Figure 125 shows the effect increasing workpiece temperature has on tool-chip interface temperatures and maximum tool forces in face milling of the various refractory metals. It can be seen that the impact force was reduced by 25% when tungsten was heated to 600°F, that a 40% reduction in impact force was experienced when tantalum or 60% tungsten - 40% molybdenum alloy was heated to around 740°F, and that 60% force reduction was obtained by heating β-titanium to 950°F. These reductions brought the impact forces closer to a normal level, as can be seen by comparison with the bar graph of force for a conventional cut under the same test conditions for B-1112, a mild steel having the commonly accepted machinability standard rating of 100% under the SAE system.

As in the case of the high strength alloys previously discussed, the amount that the tool temperature increases with an increase in workpiece temperature varies greatly, with different refractory metals being cut. For example, Figure 125 shows that with molybdenum an increase of 725°F in workpiece temperature resulted in an increase of 350°F at the tool-chip interface, whereas with tantalum an increase of 685°F at the workpiece gave a 900°F increase at the tool.

Due to the small quantities of the expensive refractory metals available, no extensive tool life studies could be made, but sufficient material was available to determine the tool life vs. work temperature relationship for 60% W - 40% MO alloy. Later a specimen of Fansteel 82, a columbium alloy, was obtained and this relationship was determined.

Figure 126 shows the effect of temperature on tool life when face milling 60% W - 40% MO at 289 fpm. It can be seen that while the machinability varied with temperature, no improvements over room temperature were found under the conditions tried.

The columbium (niobium) alloy, Fansteel 82, did however show an improvement in machinability as displayed in Figure 127. After an initial drop in tool life at low workpiece temperatures, the tool lifes increased until an optimum temperature of 1700°F was reached.

In both of these tests a tool life criterion of .015 flank wear was used to conserve material.

To prevent oxidation all heating and cutting was done in an inert argon atmosphere. The apparatus used is discussed under the section on "Heating Studies".

OBJECTIVES

The purpose of this extended program was to explore the capability of using elevated temperature machining techniques to fabricate aerospace parts from additional refractory metals and titanium alloys not originally or fully investigated.

The objectives were:

(a) Determine which refractory and titanium alloys would respond with improved machining characteristics to elevated temperature machining.

(b) Determine for each material the optimum temperature range in turning and milling.

(c) Compare cutting speed vs. tool life relationships at room temperature and optimum machining temperature.

(d) Develop suitable techniques to protect the workpiece from adverse temperature effects such as oxidation, hydrogen pick-up, etc.

(e) Determine the effect of elevated temperature on physical properties of the materials machined.

WORK MATERIALS

Based on the results of the survey of industries concerned with the fabrication of refractory and titanium alloys, the following materials were chosen for this investigation:

(1) Fansteel Metallurgical's 90% tantalum - 10% tungsten alloy

(2) Westinghouse Electric's B33 columbium alloy

(3) Climax Molybdenum's TZM molybdenum alloy

(4) General Electric's 93% theoretical density pressed and sintered unalloyed tungsten

(5) Crucible Steels' C120 AV titanium alloy

(6) Crucible Steel's B120 VCA titanium alloy.

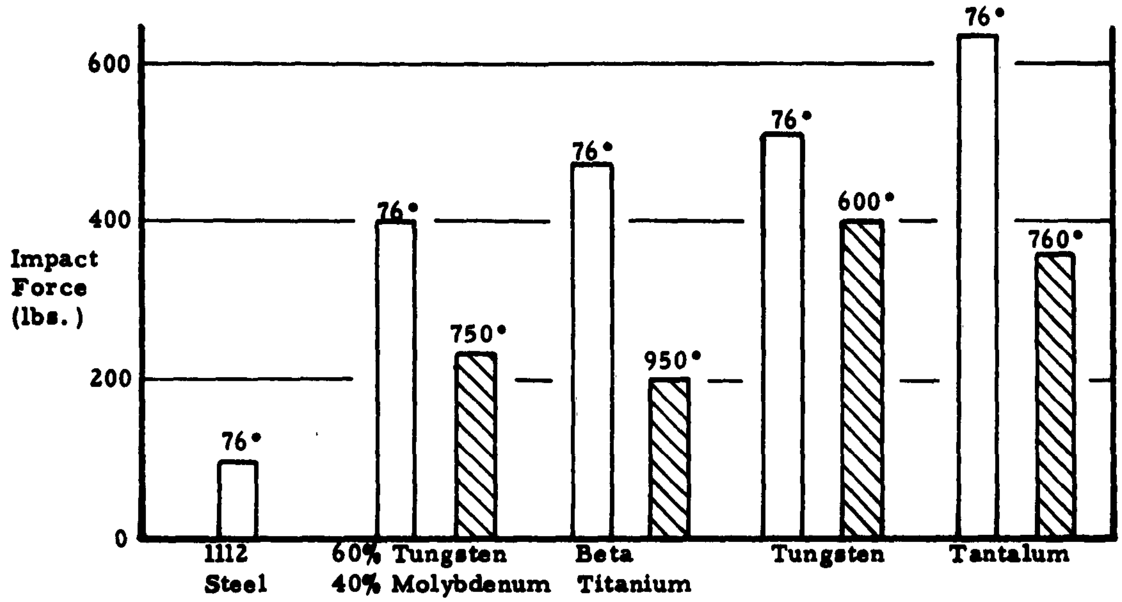
The nominal chemical compositions of these materials taken from manufacturers' data are given in Figure 128.

The size, processing history, and workpiece BHN of all workpieces as supplied are given in Figure 129.

Figures 130, 131, and 132 show the general effect of temperature on ultimate tensile strength, yield strength and ductility, respectively, of the six alloys.

A nominal comparison of important physical properties of the alloys investigated is compiled in Figure 133.

Effect of Workpiece Temperature on Maximum Tool Force
Face Milling - Refractory Materials



Cutting Speed: 98 FPM

Feed Rate: .0058 IPR

Depth of Cut: 1/32"

Effect of Workpiece Temperature on Tool Temperature
Face Milling - Refractory Materials

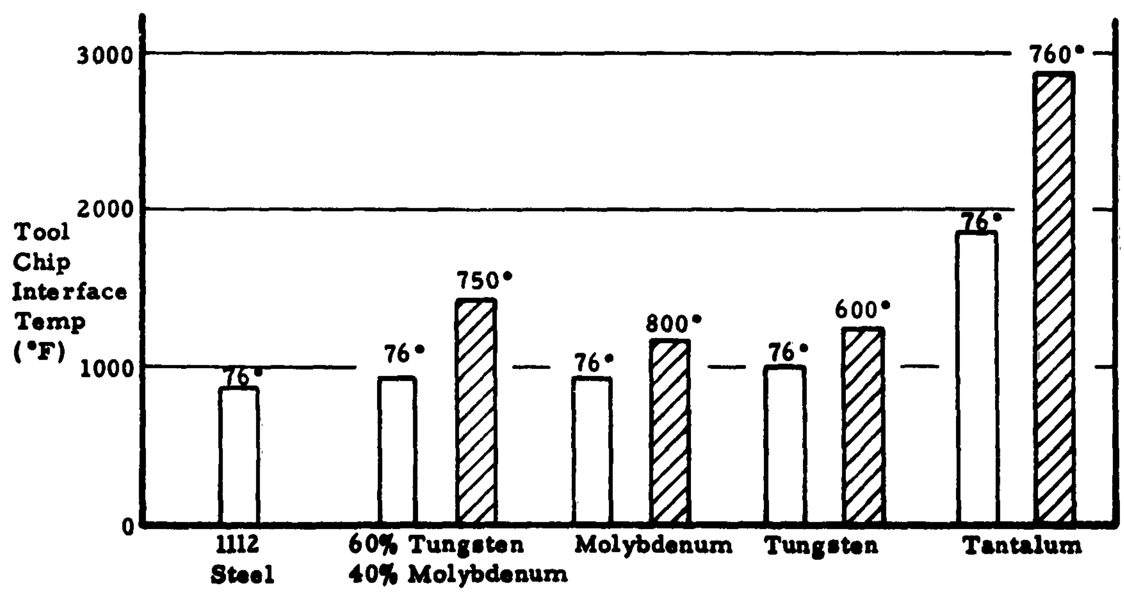


FIGURE 125

EFFECT OF TEMPERATURE ON TOOL LIFE
FACE MILLING 60% W - 40% Mo

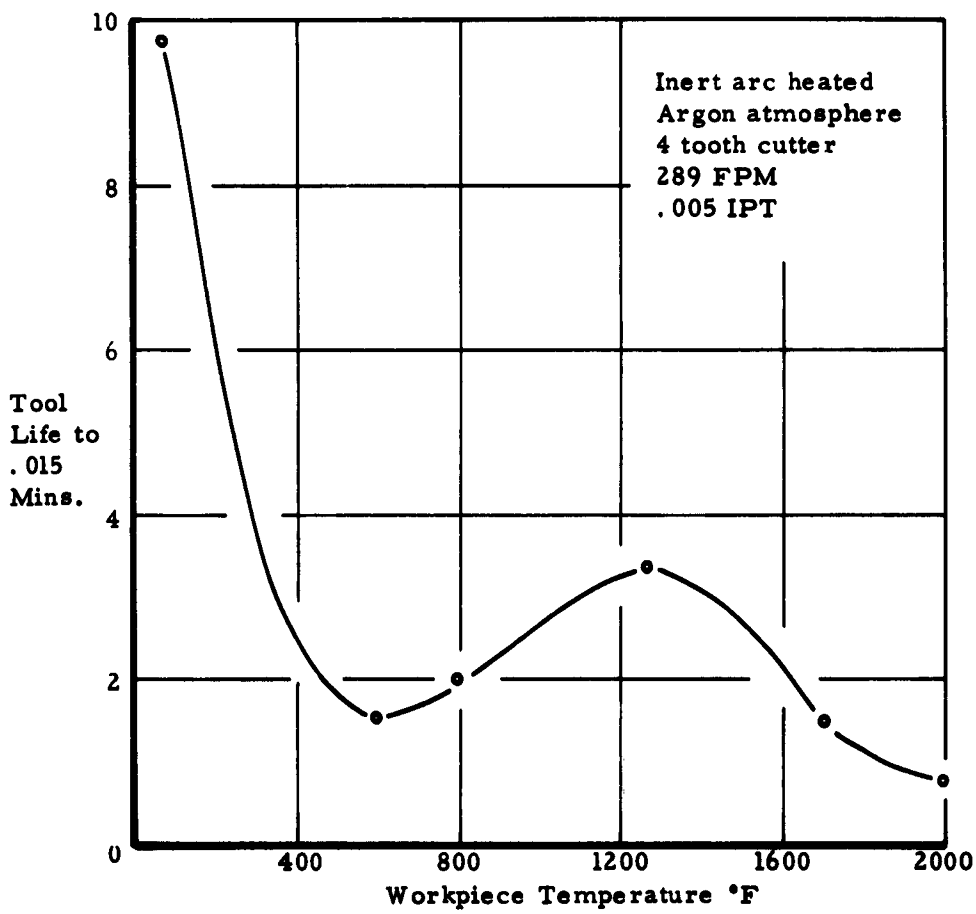


FIGURE 126

EFFECT OF TEMPERATURE ON TOOL LIFE TO .015 WEAR LAND MILLING FANSTEEL 82 COLUMBIUM (NIOBIUM)

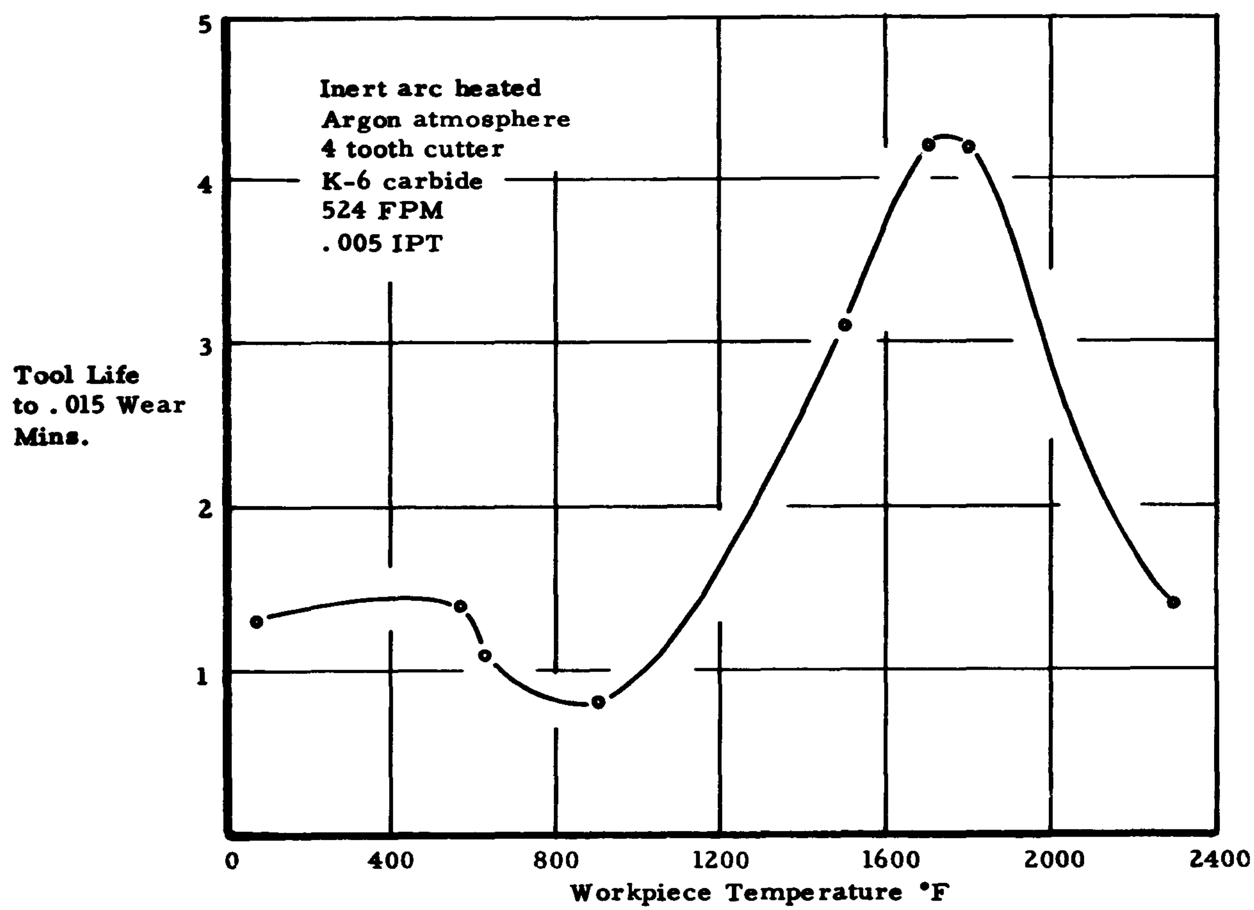


FIGURE 127

REFRACTORY AND TITANIUM ALLOYS

Alloy	% Composition
90 Ta - 10 W	90 Ta 10 W
B-33 columbium	V 5.0, O .012, N .006, C .006, Cb remainder
TZM molybdenum	Ti 0.5, Zn .08, Traces C, O, H, N, Fe, Ni, Si, Mo remainder
Unalloyed tungsten	Mo 0.02, Traces Al, Ca, Si, Fe, Cr, Ni, Cu, Mn, Mg, Sn, Bal. W
C 120 AV titanium	6.0 Al, 4.0 V, .0038 H, N 0.02, Fe 0.19, Ti remainder
B 120 VCA titanium	13.0 V, 11.0 Cr, 4.0 Al, Fe 0.27, H 2.0160, N .03, W 0.02, Mo .09, Ti remainder

FIGURE 128

SIZE, HARDNESS, AND PROCESSING HISTORY OF ALLOYS INVESTIGATED

ALLOY		SIZE AND BHN		PROCESSING HISTORY
90 Ta-10 W	Round Bar	3.375" dia. x 12" long	228 BHN	Sintered, worked, and annealed
	Flat Plate	1.025" x 7" x 7.250 long	187 BHN	
B-33 Cb	Round Bar	2.880" dia. x 12" long	183 BHN	Rolled and recrystallized
	Flat Plate	0.907" x 3.875" x 14" long	179 BHN	
TZM	Round Bar	2.385" dia. x 12" long	241 BHN	Arc cast, hot rolled, and stress relieved
	Flat Plate	1.125" x 4.125' x 12" long	255 BHN	
W	Round Bar	6.085" dia. x 12" long	321 BHN	Pressed and sintered
	Flat Plate	1.00" x 4.00" x 12" long	286-302 BHN	
C 120 AV Ti	Round Bar	6.560" dia. x 12.25" long	311 BHN	Hot rolled and annealed
	Flat Plate	1.050" x 5.125" x 24.125" long	320 BHN	
B 120 VCA Ti	Round Bar	4.530" dia. x 24" long	302 BHN	Hot rolled and annealed
	Flat Plate	1.625" x 5" x 16.187" long	277 BHN	

FIGURE 129

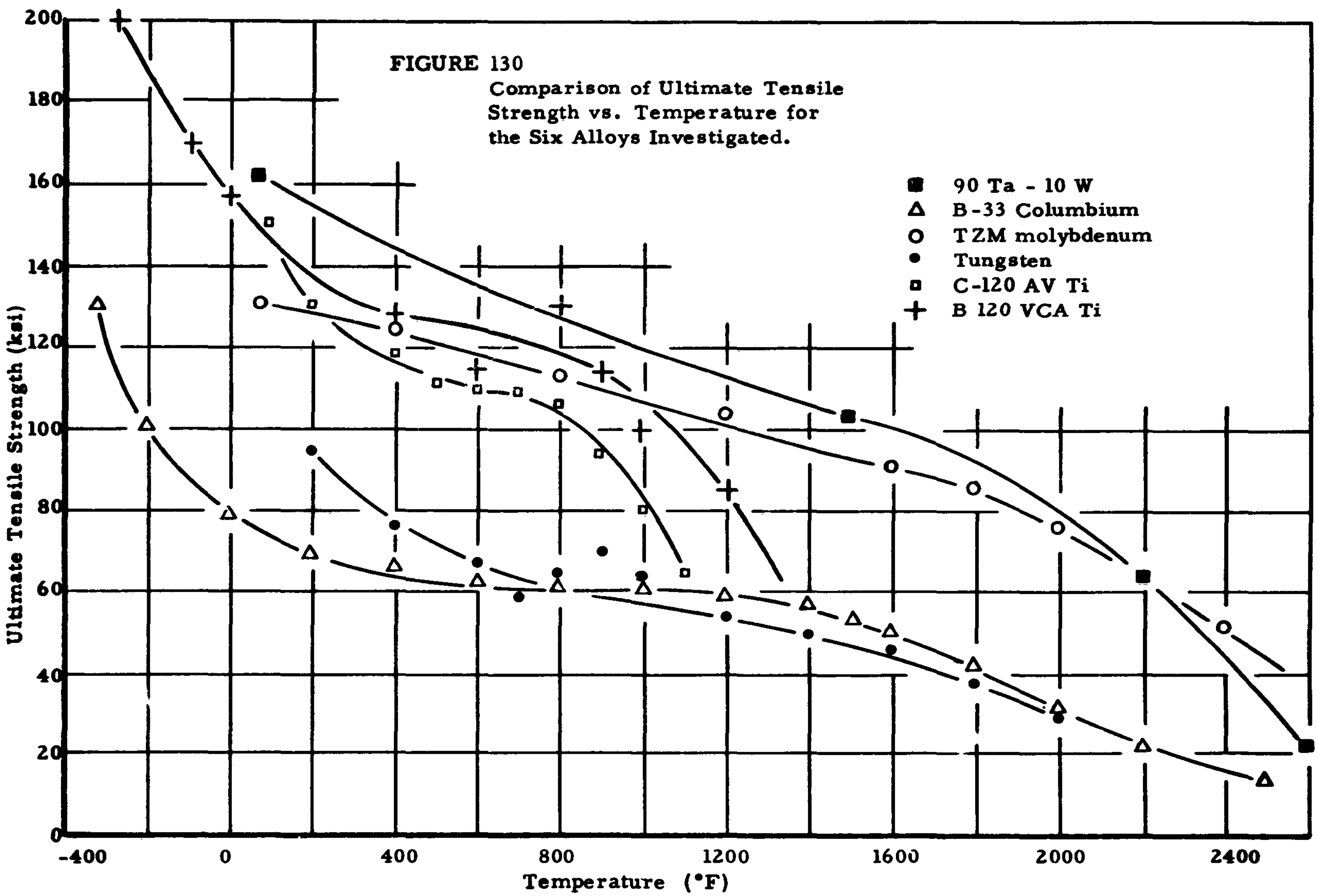


FIGURE 130
Comparison of Ultimate Tensile Strength vs. Temperature for the Six Alloys Investigated.

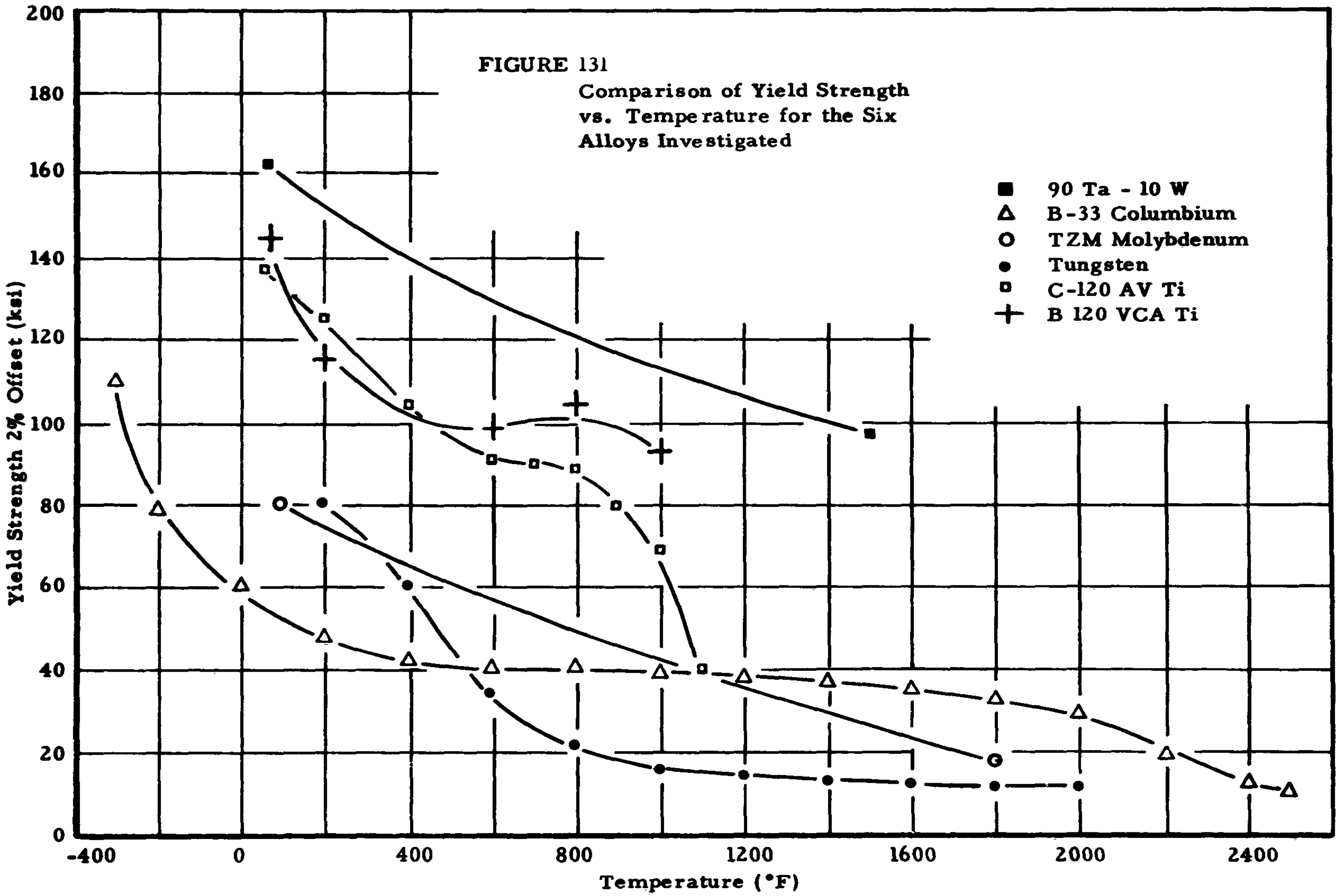


FIGURE 131
Comparison of Yield Strength vs. Temperature for the Six Alloys Investigated

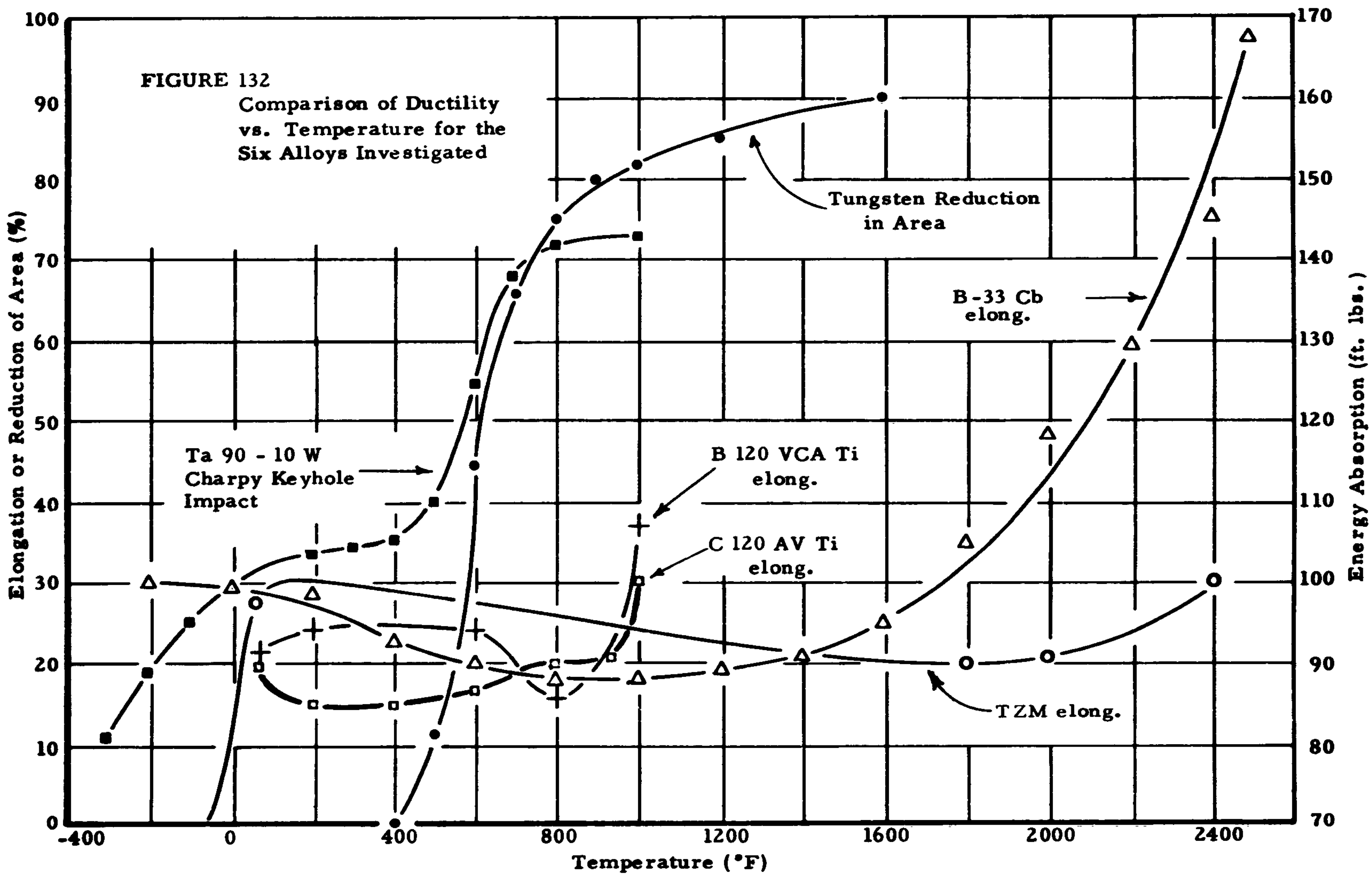


FIGURE 132
Comparison of Ductility vs. Temperature for the Six Alloys Investigated

PHYSICAL PROPERTIES

Alloy	Modulus of Elasticity psi x 10^6	Density lb/cu in.	Melting Point °F	Specific Elec. Resistivity micro ohm/cm	Specific Heat Btu/lb/°F	Thermal Cond. Btu/hr/ft^2/F	Coeff. of Thermal Exp. per °F (10^{-6})
90 Ta - 10 W	34	.600	5425	14	.110	31.4	3.84
B-33 Cb	15.8	.306	4310	21.8	.210	30.4	3.94
TZM	47	.369	4730	5.2	.198	84.5	3.02
W	52	.696	6170	5.5	.1036	96	2.47
C 120 AV Ti	15.8	163	2786-2976	176	.135	3.8	4.8
B 120 VCA Ti	14.2	.175			.130	3.7-8	5.2
1020 Steel	30	.284	2775	10-15	.376	30-40	7

FIGURE 133

INERT ARC HEATING IN TURNING REFRACTORIES
Optical Head at Left Focused on Workpiece. Rigidly Held Torch is Mounted on Lathe Carriage. Workpiece Insulated with Teflon at 3-jaw Chuck. Return Conductor also Shown at the Live Tailstock Center.

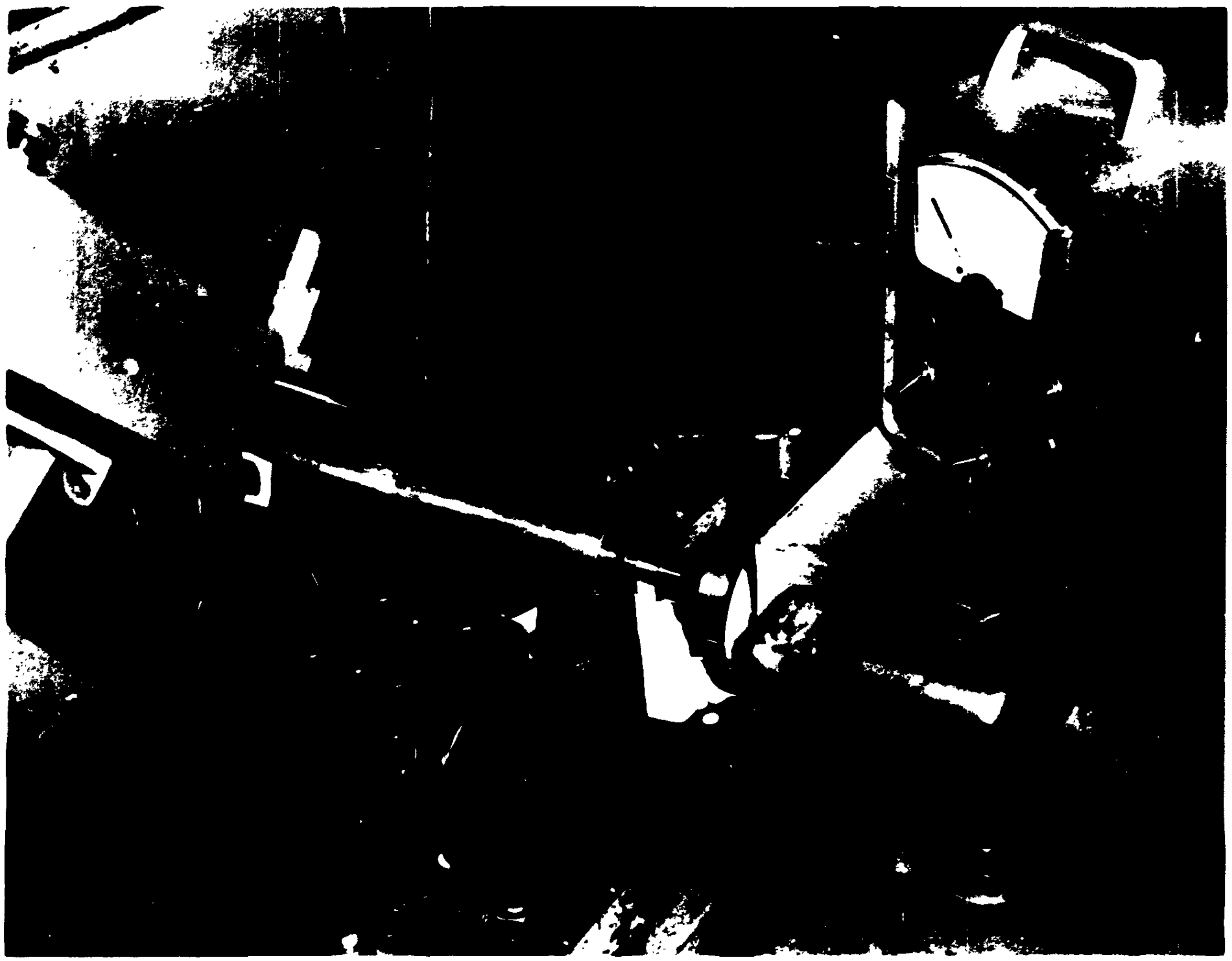


FIGURE 134

EXPERIMENTAL MACHINING

Objectives

Obtain machinability data in the form of cut speed versus tool life relationships over a wide range of workpiece temperatures to determine:

1) the optimum machining temperature for each alloy
2) the advantages and disadvantages of hot machining these alloys, developing techniques necessary for effective hot machining.

TURNING TESTS

Objectives

1) Obtain cut speed versus tool life relationships in turning each of the refractory and titanium alloys at room temperature, using optimum machining conditions as determined from Contract AF33(600)42349 and other sources.
2) Obtain workpiece temperature versus tool life relationships at the optimum room temperature cutting speed to determine the optimum turning temperature range.
3) Develop suitable techniques of workpiece temperature elevation using the tungsten inert arc torch.

Apparatus

Turning tests were carried out on the 21-1/2" Cincinnati "Traytop" lathe. A "vari-drive" arrangement enabled constant cutting speeds to be maintained regardless of workpiece diameter.

Since the materials to be tested all have low "permeability" (non-magnetic), heating methods using radio-frequency current are not effective. Therefore, an inert tungsten arc heating apparatus previously designed was modified and employed in these tests. An extensive description of this apparatus and its operation may be found under the section entitled

"Heating Studies". The arc was made self-starting, however, by superimposing a high frequency voltage over the direct heating current, eliminating the need of drawing the arc manually.

The Thermodot Model TD-6B Radiation Thermometer, capable of measuring temperatures between 170 and 5000°F was used to meter workpiece temperature. The optical head was focused on the workpiece at a point directly ahead of the cutting tool. The "target area" was so chosen that effects of chip-tool interface temperature and torch temperature on the readings could be eliminated. Figure 134 shows the typical set-up for hot turning. The optical head of the Thermodot is partially visible on the left, with the amplifier unit resting on the tailstock on the right. The inert tungsten arc torch is mounted on the lathe carriage on the opposite side of the rigidly held tool so as to move along with it and heat directly ahead of the tool. Thus, the workpiece protected the operator from the direct rays of the arc. The workpiece is shown insulated with teflon at the 3-jaw chuck and with a nylon sleeve at the live tailstock center, where the return conductor is also visible.

The following tools with corresponding geometries were available for use in the machining tests:

1) SB 42 KSBR 16C inserted tooth tool holder
   +6° SR (RR), 0° BR(AR), 15° end and side cutting
   edge angles.
2) BS 16 KSBR 16 inserted tooth tool holder
   -5° SR (RR), -5° BR(AR), 15° end and side cutting
   edge angles carbide inserts had a 1/32" nose radius.
3) BR 12 brazed carbide tip tool, K-6 grade carbide,
   modified to 20° SR (RR) and 0° BR(AR), 15° end and side
   cutting edge angles, sharp nose.

A toolmaker's microscope was used to measure flank wear, with .015" to .030" flankwear used as tool life criteria.

RESULTS AND DISCUSSION

90 Tantalum - 10 W

The tool life workpiece temperature relationship in turning 90 tantalum - 10 W is shown in Figure 135. This was obtained at 200 feet per minute using K-6 grade carbide brazed into high positive rake tool holders. Other specific cutting conditions are recorded on the graph. It is seen that tool life decreases rapidly with increasing temperature up to 800°F. Considerable cratering on the tool face was experienced along with flank wear. This is caused by the diffusion between chip and tool material at the chip-tool interface and results in chips carrying away particles of the tool. Since diffusion is temperature dependent, increasing workpiece temperature increases the "welding" tendency and thus decreases tool life. This phenomenon was expected with tantalum; it can be reduced by proper selection of a cutting fluid for room temperature machining.

Dry, room temperature turning tool lives correlated with those obtained by Metcut in spite of their use of a cutting fluid under otherwise similar conditions. Surface finish obtained was good, with only slight discoloration at higher temperatures. The evaluation of workpiece temperatures greater than 800°F was precluded by the lack of adequate protection of the workpiece from oxidation. Higher temperatures can be investigated in milling because of successful inert atmosphere protection techniques.

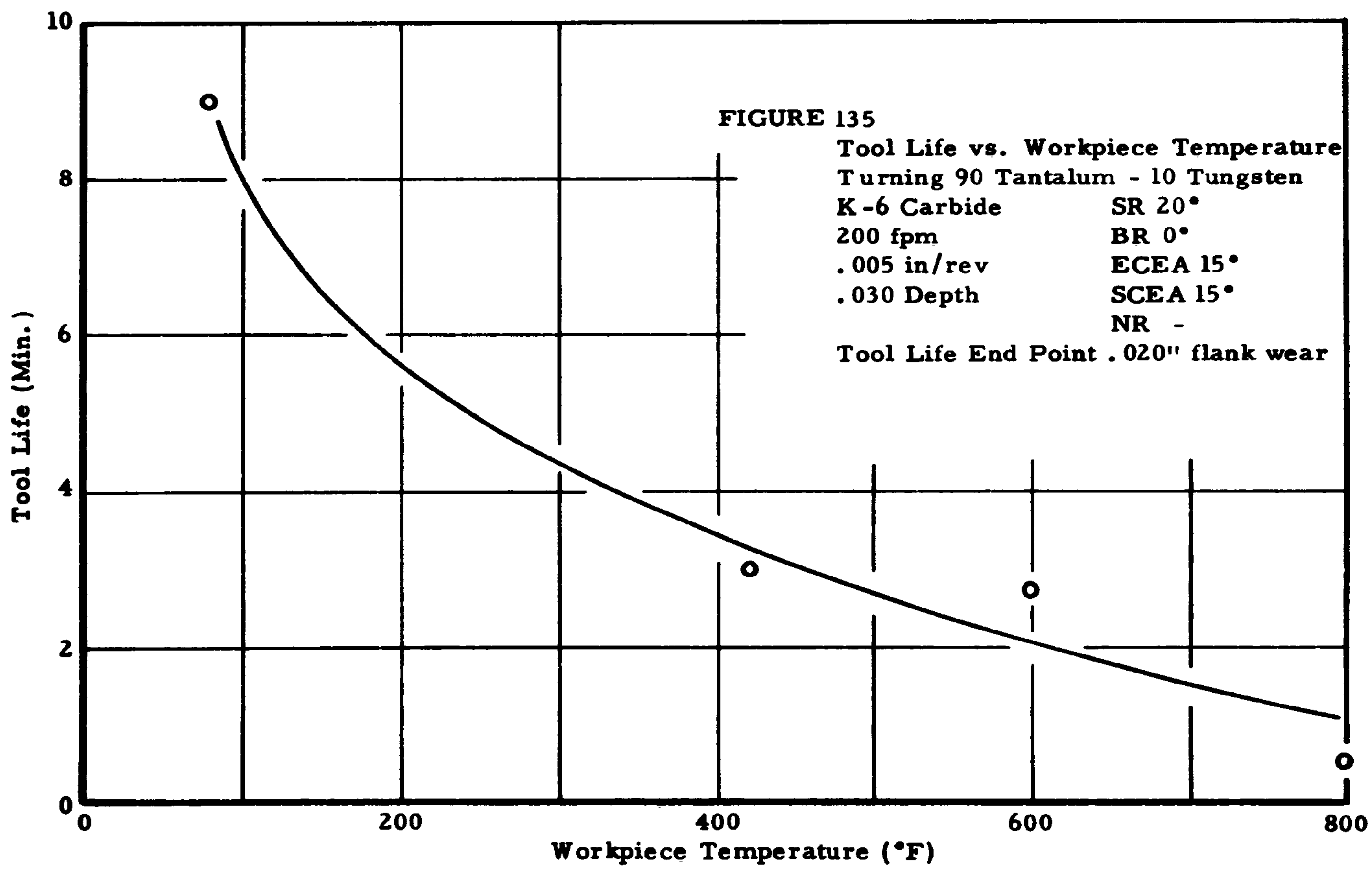


FIGURE 135

Tool Life vs. Workpiece Temperature
Turning 90 Tantalum - 10 Tungsten

K-6 Carbide	SR 20°
200 fpm	BR 0°
.005 in/rev	ECEA 15°
.030 Depth	SCEA 15°
	NR -

Tool Life End Point .020" flank wear

B-33 Columbium

This alloy shows a similar decrease in tool life with increasing temperature as indicated in Figure 136. Specific cutting conditions, as recorded on the graph, were taken from recommendations from various sources. Room temperature tool life for B-33 columbium was greater than for 90 tantalum - 10 tungsten alloy under similar conditions. Metcut's work with D-31 columbium yielded much higher tool lives at room temperature with coolant than could be obtained dry turning B-33 columbium. Good surface finish was obtained under these conditions of dry turning.

Like tantalum, columbium exhibited the same "welding" tendency. Higher workpiece temperature served only to increase this tendency and, therefore, lowered tool life.

It is interesting to note that the chips resulting from turning at high workpiece temperatures were considerably thicker than those obtained at room temperature under otherwise similar conditions. This indicates that the application of external heat was accompanied by a decrease in the shear angle and, according to Merchant[43], an increase in tool-chip friction. Thus, the disadvantage of hot machining was realized: the increase of tool-chip interface temperature without the advantages of a significant decrease in workpiece strength.

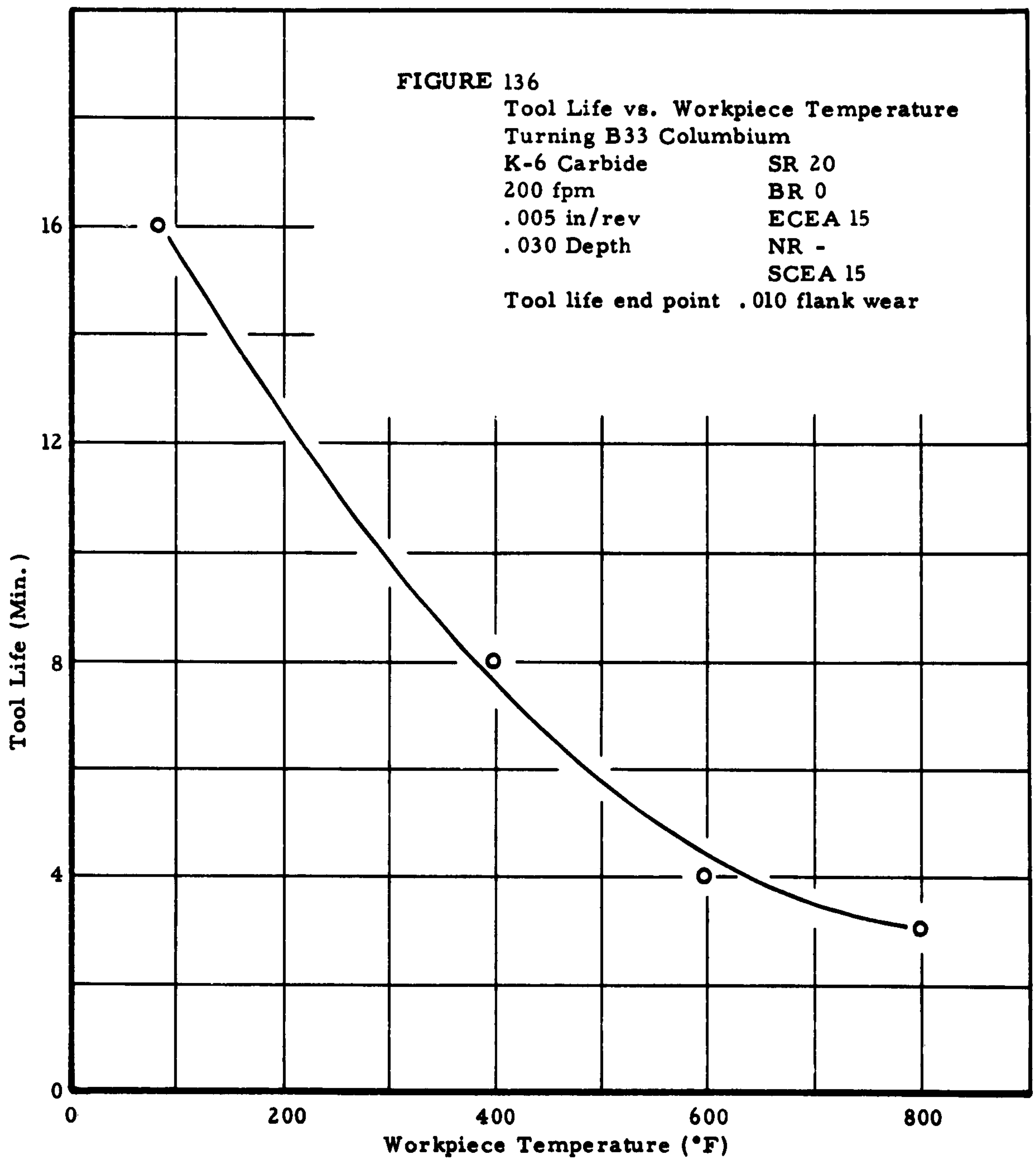


FIGURE 136
Tool Life vs. Workpiece Temperature
Turning B33 Columbium
K-6 Carbide
SR 20
200 fpm
BR 0
.005 in/rev
ECEA 15
.030 Depth
NR -
SCEA 15
Tool life end point .010 flank wear
16
12
8
4
0
Tool Life (Min.)
0
200
400
600
800
Workpiece Temperature (°F)

TZM Molybdenum

Tool life workpiece temperature relationship for turning TZM alloy is given in Figure 137. Dry, room temperature tool life obtained was not as great as that listed by Metcut when using a cutting fluid. Tool life decreased drastically as workpiece temperature was increased. This is due, it is felt, to the small loss in strength that the TZM alloy exhibits with increased temperature, while higher chip-tool interface temperatures cause increasing detrimental effects on tool life. Room temperature turning, as well as elevated temperature turning, involved workpiece temperatures well above the brittle-ductile transition temperature range for the TZM alloy, obviating any tool life increase which might be realized by turning slightly above this transition temperature. The temperature range tested was limited by oxidation considerations.

Surface finish at 300 fpm dry was acceptable.

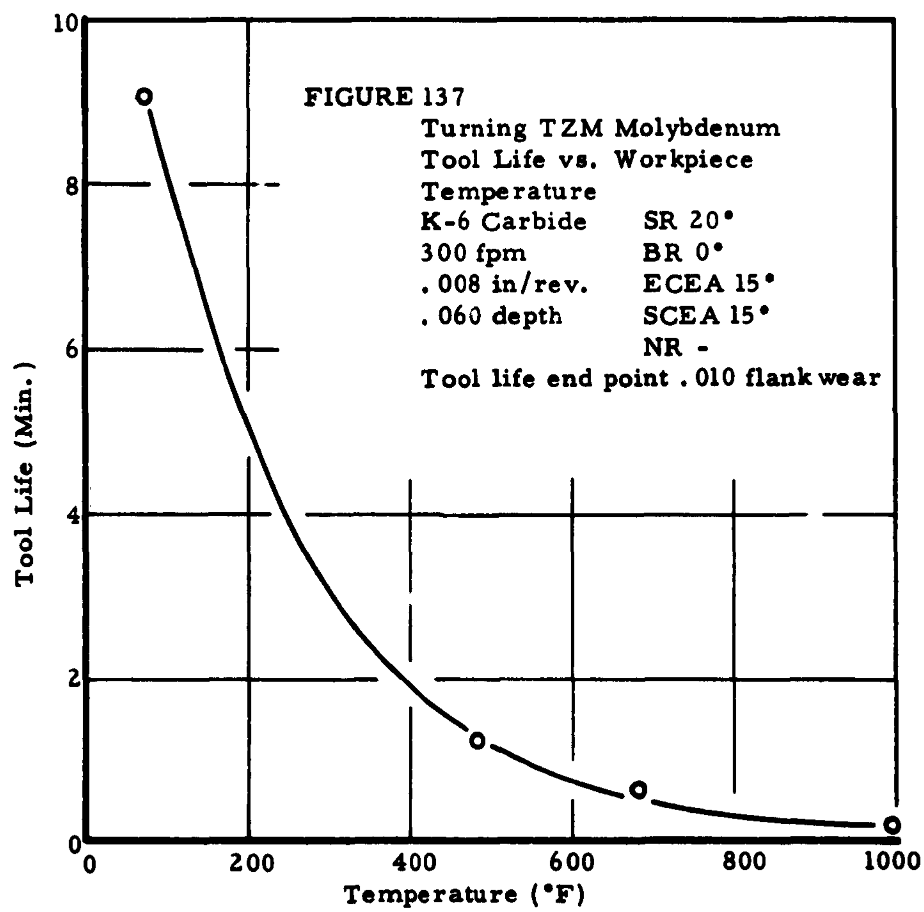


FIGURE 137
Turning TZM Molybdenum
Tool Life vs. Workpiece
Temperature
K-6 Carbide SR 20°
300 fpm BR 0°
.008 in/rev. ECEA 15°
.060 depth SCEA 15°
NR -
Tool life end point .010 flank wear
10
8
6
4
2
0
0
200
400
600
800
1000
Tool Life (Min.)
Temperature (°F)

Tungsten

Since tungsten commands special importance in the aerospace field, its machinability characteristics were thoroughly evaluated.

With recommended feeds of approximately .008 inches/revolution and .050 inches depth of cut, cut speed versus tool life tests over a wide range of grades of carbide, including K-6, K-8, K-11, 350, and 370, were made dry at room temperature. All the tool lives obtained were very low, on the order of one minute.

Since Metcut reported higher tool lives with a cutting fluid under otherwise identical conditions, additional tests were performed to evaluate the effect of cutting fluid on tool life. Cut speed versus tool life curves were obtained using: 1) soluble oil similar to that employed by Metcut, and 2) a chemical water base cutting fluid. These results are shown in Figure 138, with other specific cutting conditions as recorded. It is seen that, while soluble oil was ineffective, the chemical water base cutting fluid results correlated very well to Metcut's curve. Also, surface finish was highly acceptable with few microcracks remaining. It is clear then that the variable mechanical properties found in tungsten bars, consolidated by powder metallurgy methods, necessitate the individual selection of a cutting fluid to achieve maximum tool life.

Hot turning tungsten (600°-800°F) in the cut speed ranges of Figure 138, using K-11 inserts, showed no significant tool life improvement. Some oxidation and severe heat checking was experienced at these temperatures, sometimes with drastic results, Figure 139. Ceramic inserts were also tried to take advantage of their superior elevated temperature strength where carbide inserts show rapid wear. An excellent surface finish was obtained with these ceramic inserts at higher cut speeds, but tool life was still low.

It is common knowledge that the Type 2 or continuous chip, indicates the most efficient machining conditions. This type of chip is usually obtained in machining ductile materials. Since tungsten's brittle-ductile transition occurs around 450°F, some tool life improvement might be expected when the tungsten is heated above this temperature and is, therefore, ductile. But previous tests at 100-300 fpm and 600-800°F produced no tool life improvement. However, it is felt, that in these cases, the high workpiece temperature, in addition to the high "self-induced" temperatures, were too severe for the tool. Perhaps, if the heat input was limited by: 1) heating to only 450°F or just into tungsten's ductile temperature range, and 2) using low cut speeds to minimize the self-induced temperature, tool lives could be increased. Such was found to be the case.

Figure 138 shows hot turning tool lives (500°F) at speeds between 20-70 fpm to be comparable to those obtained by higher speed turning with a properly selected cutting fluid. However, Figure 140 indicates that the latter is superior when cubic inches of metal removed are considered. Measurement of workpiece temperature with a Thermodot radiation thermometer during so-called "room temperature" turning indicates temperatures in the 300-500 degree range. This temperature range of turning should actually be regarded as "hot" machining, even though no heat was added externally. Relatively ductile chips formed in turning the tungsten at 200 fpm verifies this reasoning. The self-induced temperature placed the tungsten workpiece beyond the brittle-ductile transition range, ($\sim$450°F). Where cut speeds were low (50 fpm), indicated workpiece temperature was less than 200°F during turning, well below the brittle-ductile temperature range for tungsten. Accordingly, the chips formed were powdery and brittle.

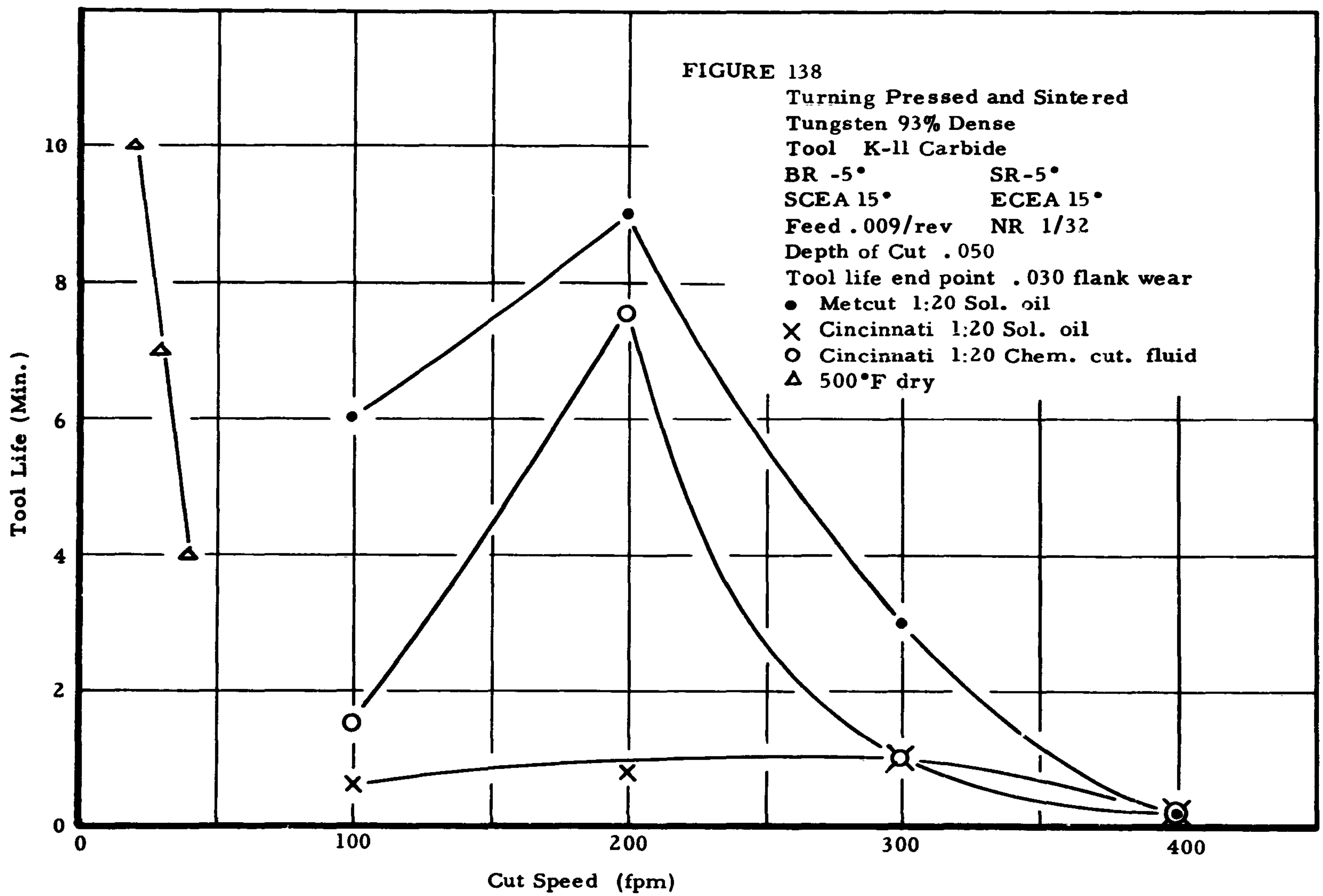


FIGURE 138
Turning Pressed and Sintered
Tungsten 93% Dense
Tool K-11 Carbide
BR -5° SR-5°
SCEA 15° ECEA 15°
Feed .009/rev NR 1/32
Depth of Cut .050
Tool life end point .030 flank wear
• Metcut 1:20 Sol. oil
X Cincinnati 1:20 Sol. oil
O Cincinnati 1:20 Chem. cut. fluid
Δ 500°F dry
Tool Life (Min.)
0
2
4
6
8
10
Cut Speed (fpm)
0
100
200
300
400

HEAT CHECKING OF TUNGSTEN WORKPIECE AT ELEVATED TEMPERATURE

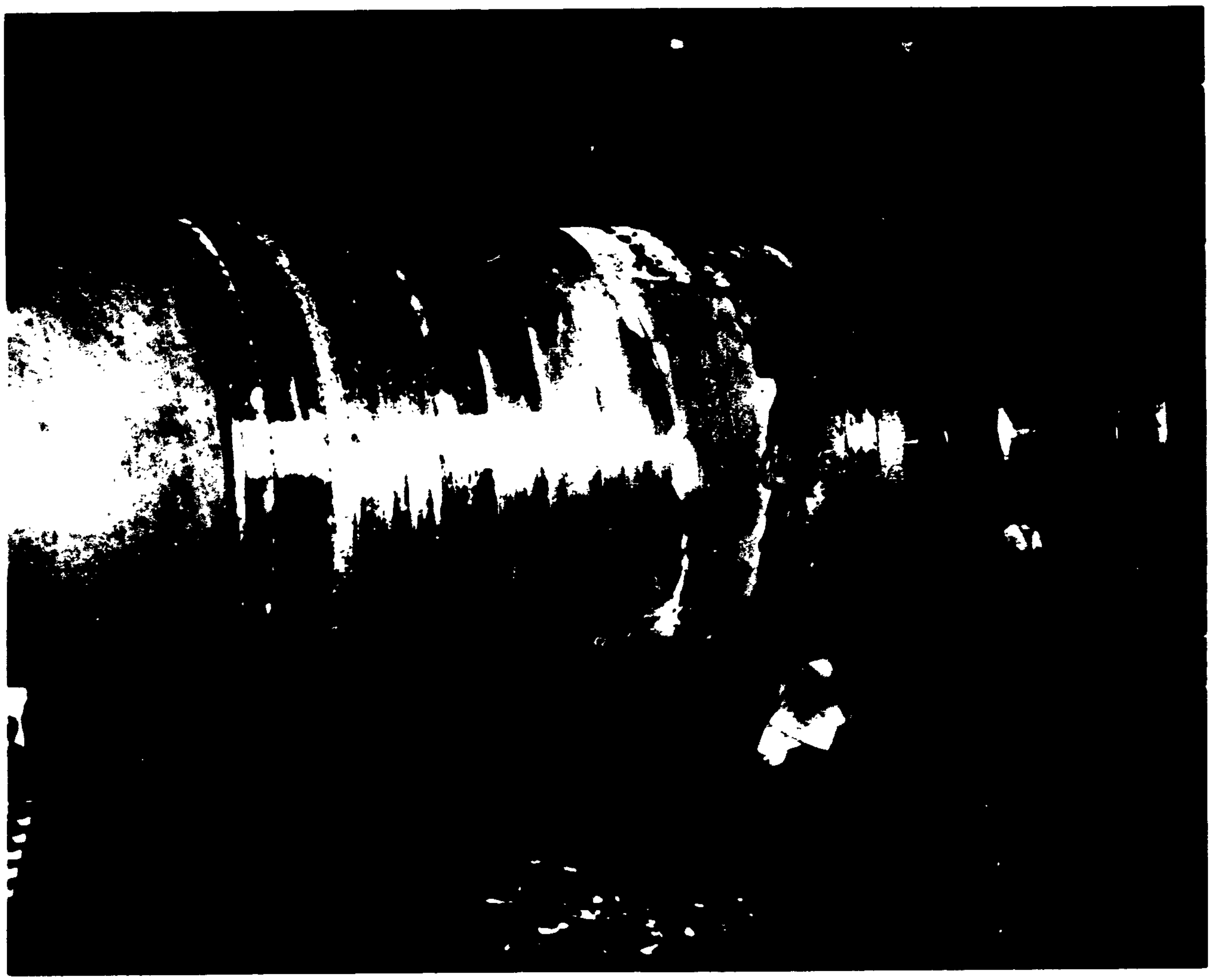


FIGURE 139

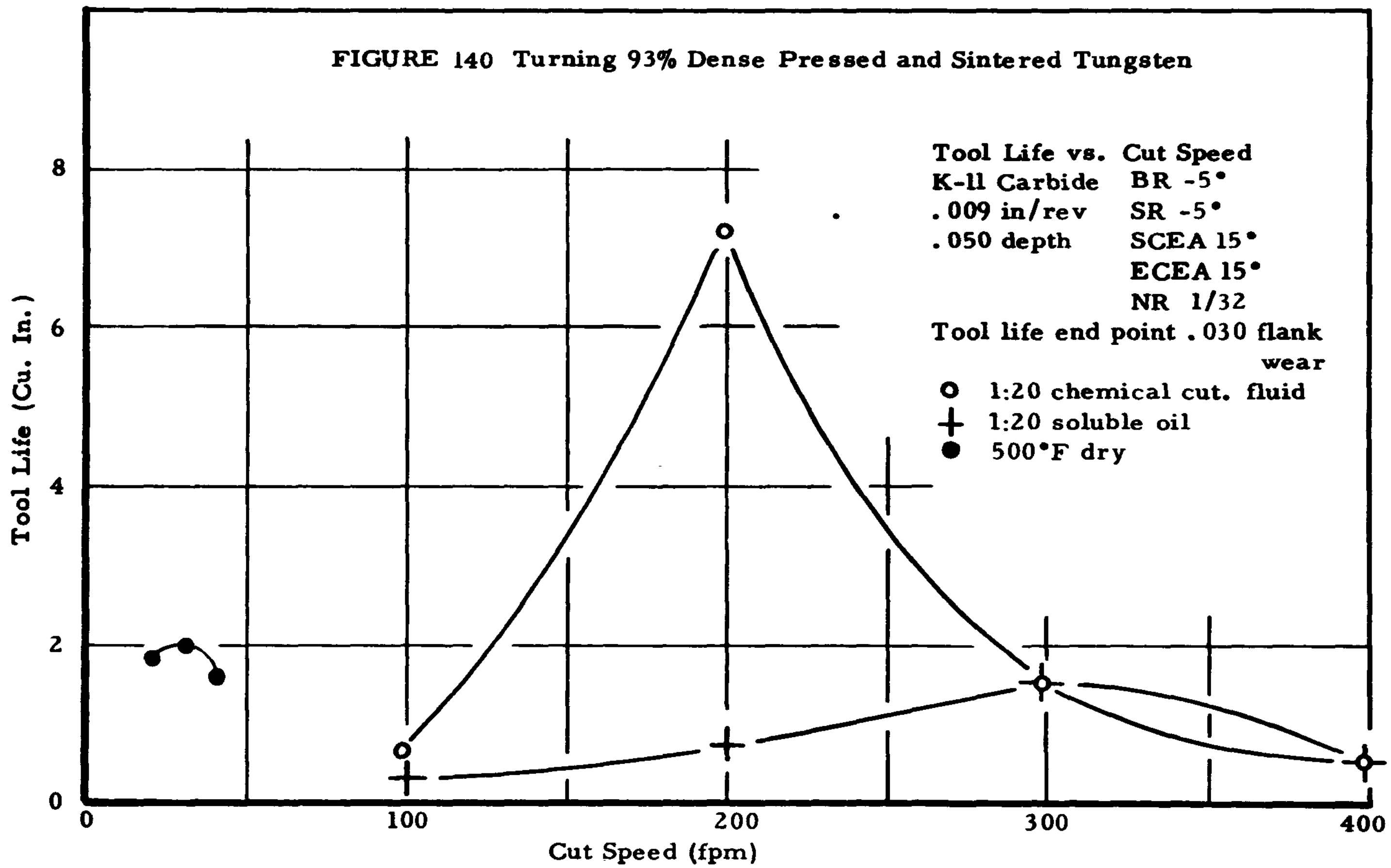


FIGURE 140 Turning 93% Dense Pressed and Sintered Tungsten

C 120 AV Titanium

The tool life workpiece temperature relationship for turning C 120 AV titanium is given in Figure 141. It is seen that room temperature dry turning resulted in a reasonable tool life of approximately 12 minutes. This compares favorably with Metcut's tool life under the same turning conditions using a cutting fluid.

However, tool life fell off as the workpiece temperature was elevated. This is explained by the affinity which titanium has for other metals. Increasing the workpiece temperature, therefore, increases the tendency for titanium to weld itself to the cutting edge, and results in very rapid wear.

Titanium produces a large increase in tool-chip interface temperature for a given increase in workpiece temperature. This has been shown[44] to be due to titanium's low thermal diffusivity, high chip flow velocity, and small chip contact area during machining. Thus, the value of using a cutting fluid when machining titanium is readily appreciated. In fact, tool lives of 60-70 minutes were obtained by Metcut under the same turning conditions described above with a cutting fluid, after a cut speed reduction to about 165 fpm.

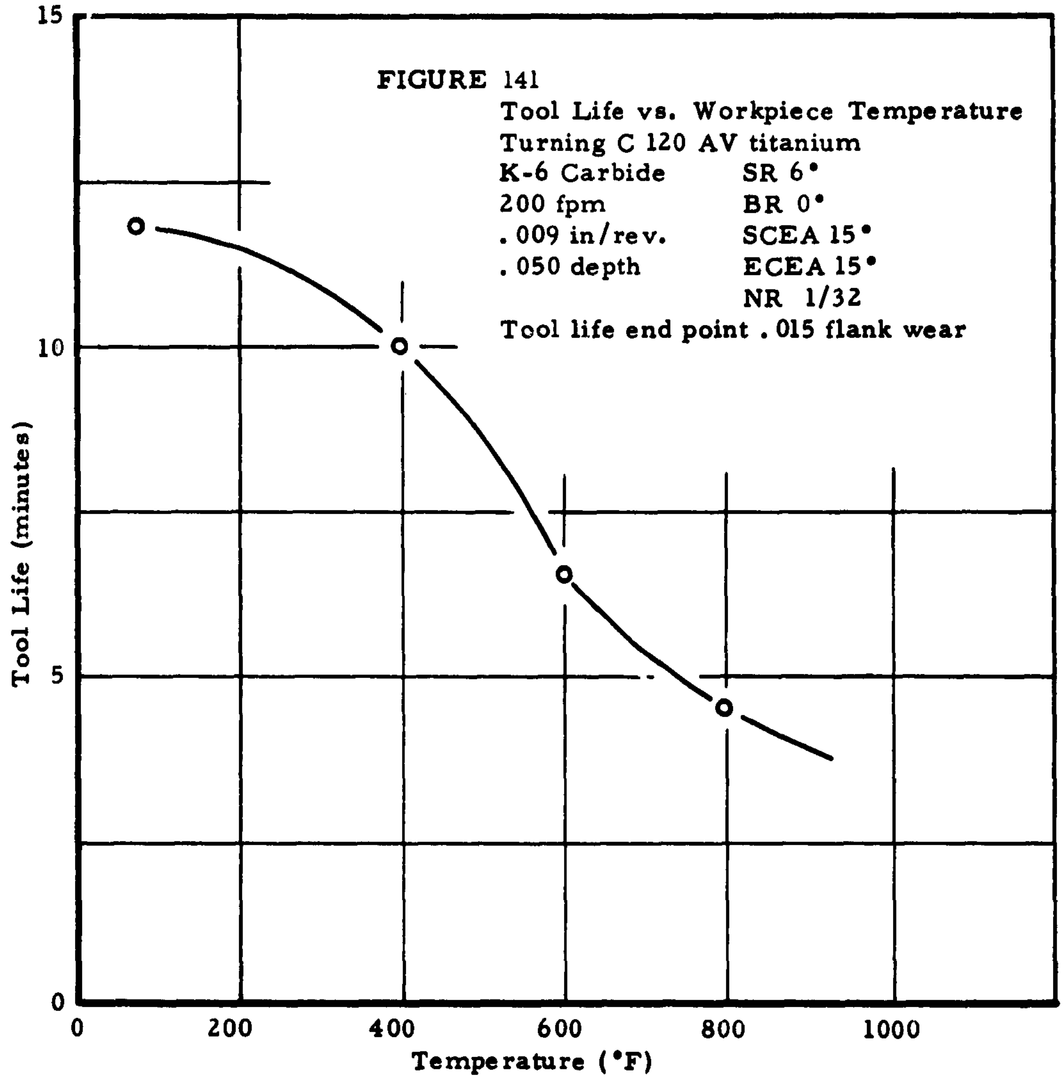


FIGURE 141
Tool Life vs. Workpiece Temperature
Turning C 120 AV titanium
K-6 Carbide
SR 6°
200 fpm
BR 0°
.009 in/rev.
SCEA 15°
.050 depth
ECEA 15°
NR 1/32
Tool life end point .015 flank wear
15
10
5
0
Tool Life (minutes)
0
200
400
600
800
1000
Temperature (°F)

B 120 VCA Titanium

Since B 120 VCA titanium has only recently become commercially available, references to previous machinability data were limited. For this reason, a tool life cutting speed relationship for dry turning this alloy was obtained, and is given in Figure 142. Other specific cutting conditions as recorded were chosen from experience with C 120 AV titanium and recommendations from other sources[63]. It is seen that only 50 fpm yielded a reasonable tool life, with higher speeds resulting in very rapid wear and tool notching at the depth of cut. The tendency of this alloy to work harden during machining and leave a hard case on the surface is thought to be the cause of this notching.

Tool life workpiece temperature relationship for turning B 120 VCA titanium is given in Figure 143. Again, an increase in workpiece temperature resulted in a decrease in tool life, for the most part due to the same machining characteristics inherent in all titanium base alloys.

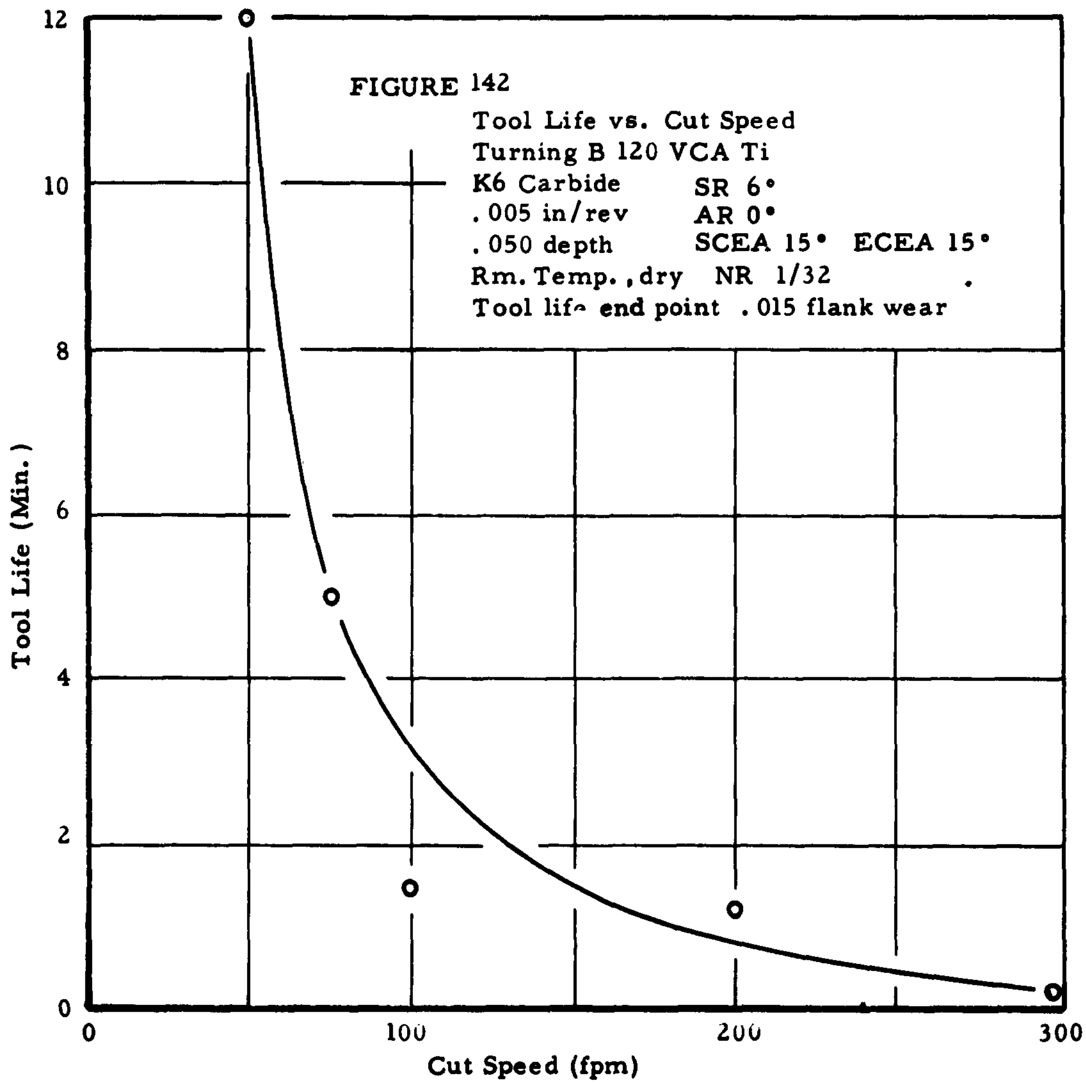


FIGURE 142
Tool Life vs. Cut Speed
Turning B 120 VCA Ti
K6 Carbide SR 6°
. 005 in/rev AR 0°
. 050 depth SCEA 15° ECEA 15°
Rm. Temp., dry NR 1/32
Tool lif^ end point . 015 flank wear
Tool Life (Min.)
12
10
8
6
4
2
0
0
100
200
300
Cut Speed (fpm)

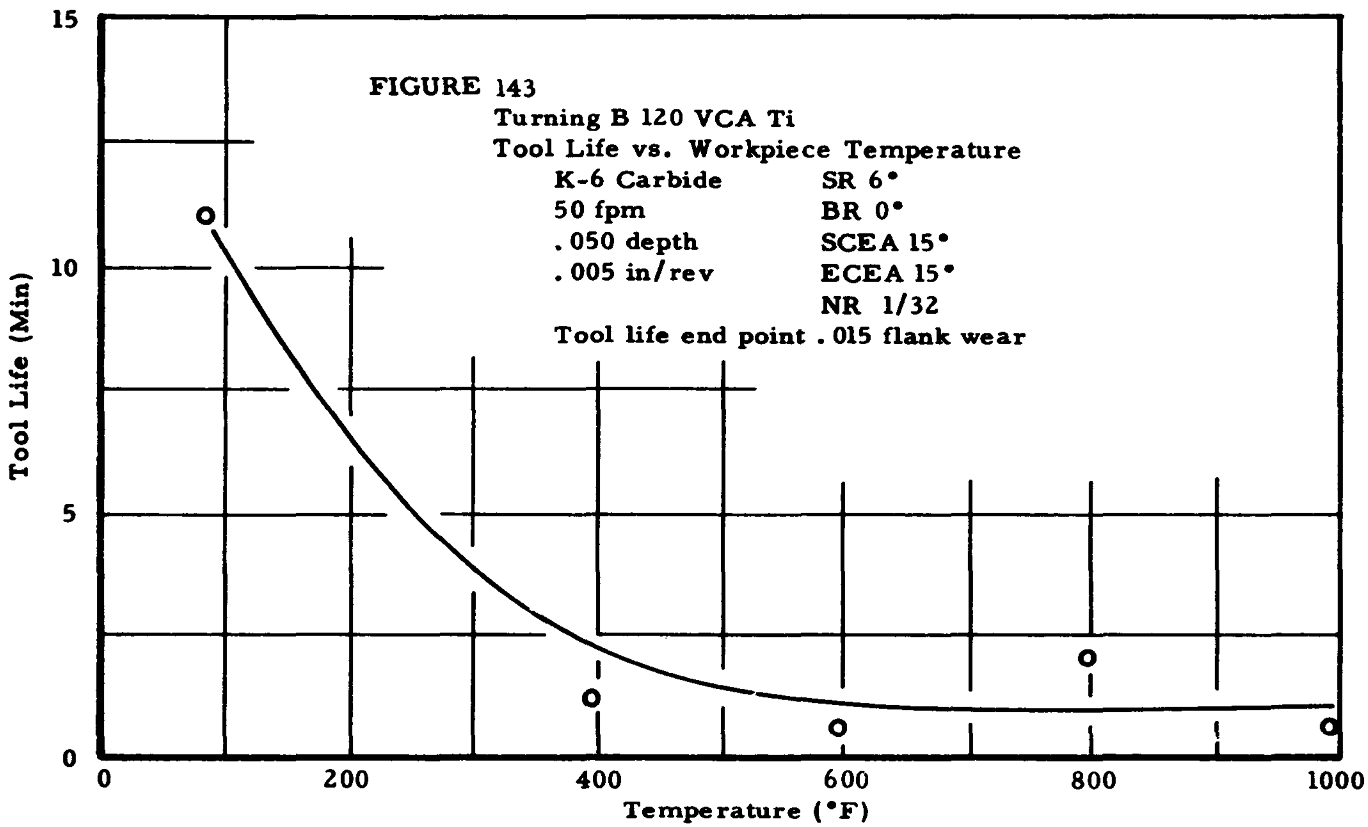


FIGURE 143
Turning B 120 VCA Ti
Tool Life vs. Workpiece Temperature

K-6 Carbide	SR 6°
50 fpm	BR 0°
.050 depth	SCEA 15°
.005 in/rev	ECEA 15°
	NR 1/32

Tool life end point .015 flank wear

MILLING TESTS

Objectives

1) Obtain cut speed vs. tool life relationships in milling each of the refractory and titanium alloys at room temperature, using optimum machining conditions as determined from Contract AF33(600)42349 and other sources.

2) Obtain workpiece temperature versus tool life relationships at the optimum cutting speed to determine the optimum milling temperature range.

3) Develop suitable techniques for workpiece temperature elevation using the inert tungsten arc torch.

4) Develop methods and apparatus effective in protecting exposed portions of the workpiece from oxidation or other contamination at elevated temperatures.

5) Examine the effect of elevated temperature machining on breakout commonly experienced during interrupted cutting of tungsten and molybdenum.

Apparatus

Milling tests were performed on a Cincinnati No. 4 Dual Power Vertical Milling Machine. The workpieces were clamped in and insulated from a vice mounted on the machine table. Heating was supplied by the tungsten inert arc torch as previously described. The torch was held in a specially designed holder. A slide-crank mechanism permitted the torch to reciprocate back and forth across the width of the workpiece. The connecting link could be pinned at various radii to the circular steel crank disk to provide a range of torch strokes. The disk was rotated by a flexible shaft connected to a Graham variable speed transmission which was in turn driven by a 1/4 hp A. C. motor. The motor-transmission unit was mounted on top of the milling machine for convenience. The fixture was adjustable to vary the engagement angle and distance of the torch from the cutter.

Fiberboard shielding protected the operator from the arc when machining, and a welding hood was used when examining the arc. The Thermodot Radiation Thermometer was again used to measure workpiece temperature.

For elevated temperature testing above oxidizing temperatures for the metals, means were provided to continuously bathe the hot workpiece with an atmosphere of inert argon gas. This was accomplished by connecting a perforated metal tubular loop placed around and slightly below the surface to be cut. The tubular loop was connected to a cylinder of argon gas. A regulator was set to insure a continuous gas flow which would then completely purge the critical area of air. This eliminate the use of the awkward "swimming pool" arrangement initially used to prevent oxidization.

The face milling cutter used the same "throwaway" insert tool holders described in the turning apparatus description. A picture of the entire set-up is given in Figure 144.

HOT MILLING WITH INERT TUNGSTEN ARC HEATING
Relative Positions of Radiation Thermometer, Torch, and
Oscillating Mechanism to the Cutter

FIGURE 144

RESULTS AND DISCUSSION

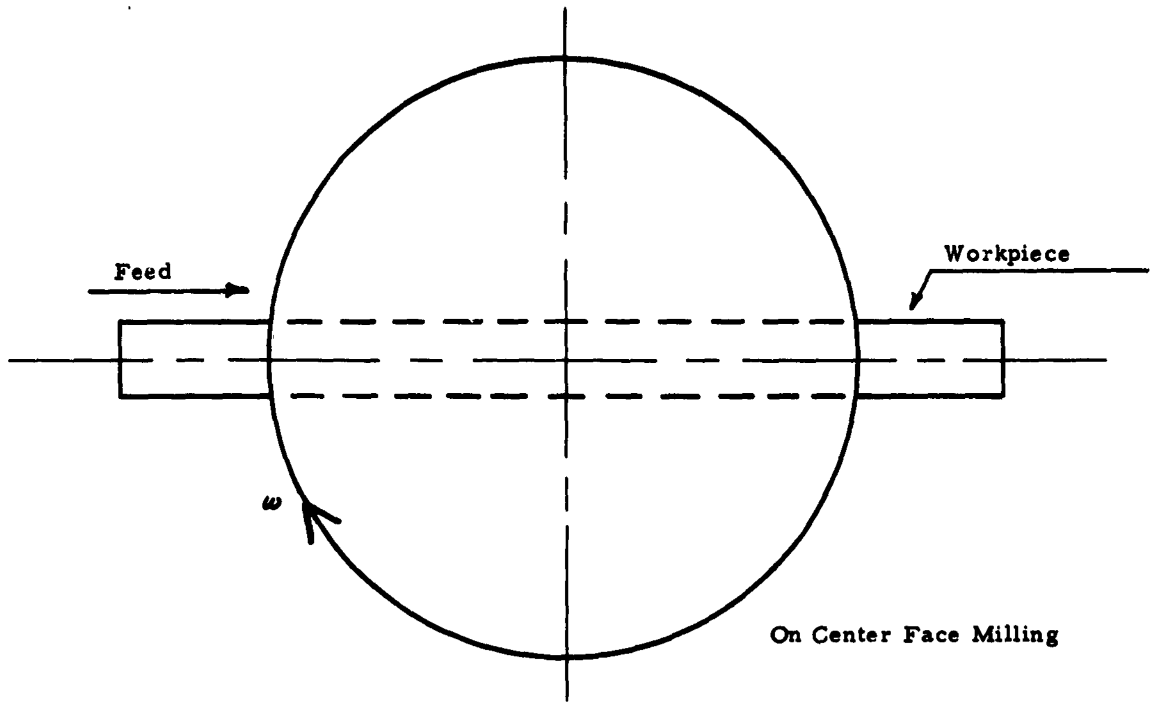
90 Tantalum - 10 W

As can be noted in Figure 129, the flat plates of each material vary in width. For convenience, therefore, tool life in milling was measured in cubic inches of metal removed with a specified amount of flank wear.

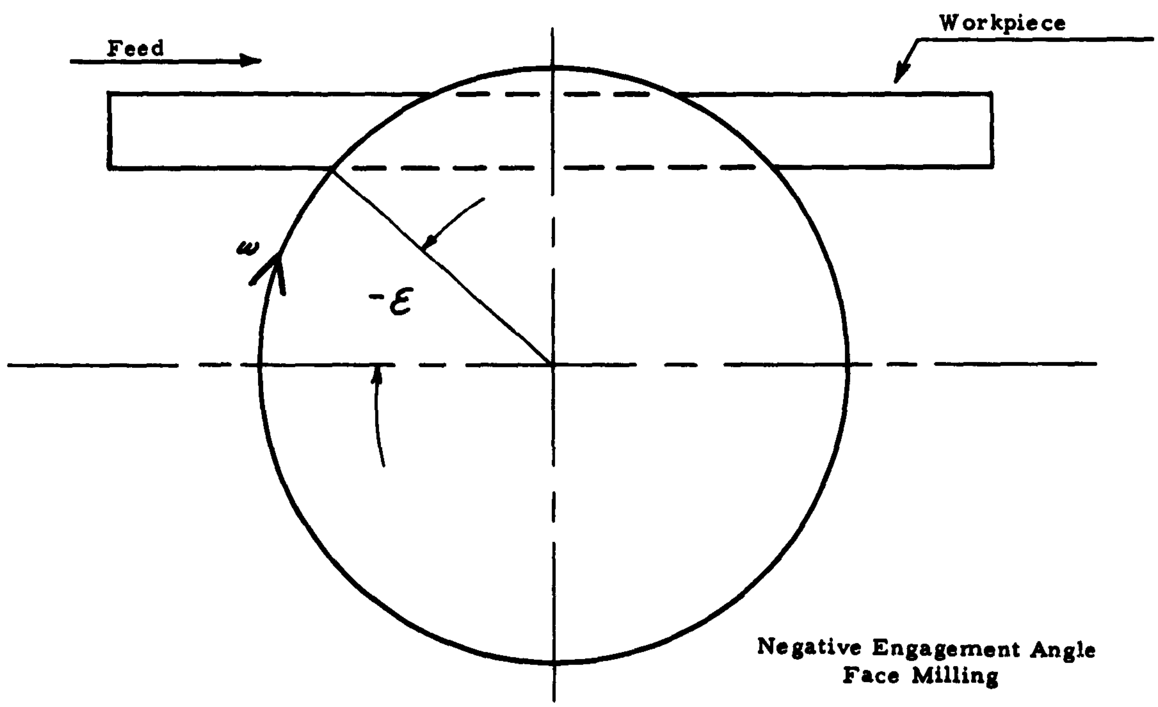
Since tool wear was expected to be primarily due to the "welding" tendency, which the 90 Ta - 10 W exhibited in turning, a "chip plucker" was designed and used in all tests. Thereby, the chip which "froze" to the cutting edge as the tooth left the workpiece, was removed before the cutter carried it around to crush it against the workpiece at the tooth entry into the cut.

Initial cutting conditions, which included K-6 grade 6° RR, 0° AR carbide tools, 100-200 cut speed, .005 chip/tooth, .050 depth of cut, and "on center" dry, room temperature milling, resulted in severe nose breakdown. This correlates with results in Contract AF33(600)42349. This tendency was significantly reduced by switiching to a highly negative engagement angle as shown in Figure 145. Thus, chip thickness at tooth exit was very small and welding of the chip to the tool was accordingly discouraged. In addition, brazed carbide tip tools ground to +20° side rake were used to reduce the heat generated during the actual cutting. At approximately 200 fpm, measurable tool lives were obtained.

Figure 146 gives the tool life workpiece temperature relationship obtained for 90 Ta - 10 W. Tool life increased slightly at approximately 400°F but fell off rapidly as the workpiece temperature was further increased. Severe welding occurs around 1000°F, obviating any possible benefit beyond this temperature. This is due, in part, to the large increase of tool-chip interface temperature for a given rise in workpiece temperature which tantalum exhibits, as is shown on page 223.



On Center Face Milling



Negative Engagement Angle
Face Milling

FIGURE 145

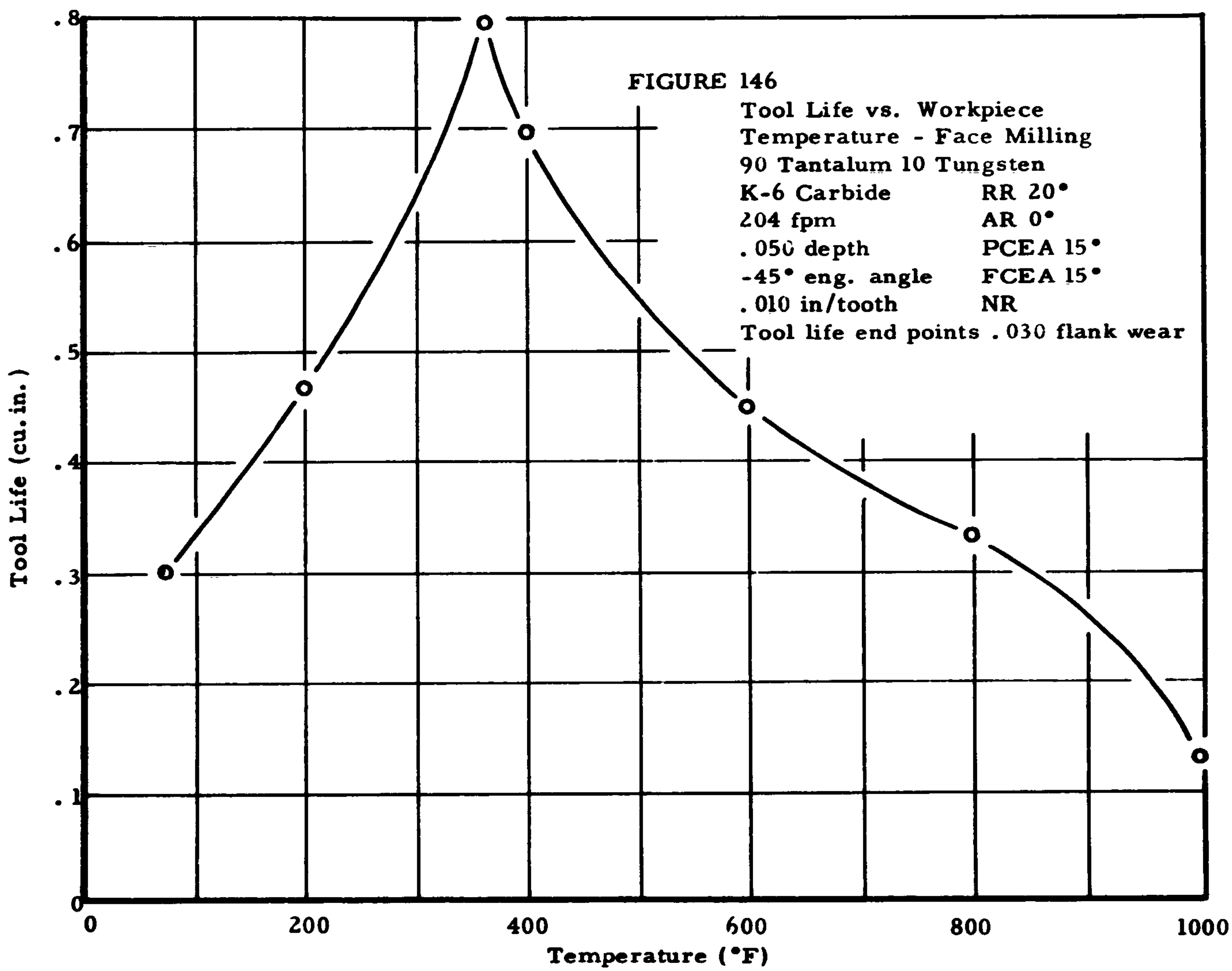


FIGURE 146
Tool Life vs. Workpiece
Temperature - Face Milling
90 Tantalum 10 Tungsten

K-6 Carbide	RR 20°
204 fpm	AR 0°
.050 depth	PCEA 15°
-45° eng. angle	FCEA 15°
.010 in/tooth	NR

Tool life end points .030 flank wear

B-33 Columbium

Columbium has similar machining characteristics to tantalum in that the same chip-tool welding tendency is exhibited; therefore, similar measures were taken to overcome this tendency. The tool life cutting speed relationship obtained in dry, room temperature face milling of B-33 columbium is given in Figure 147. Obviously columbium yields a much longer tool life under these conditions than does tantalum.

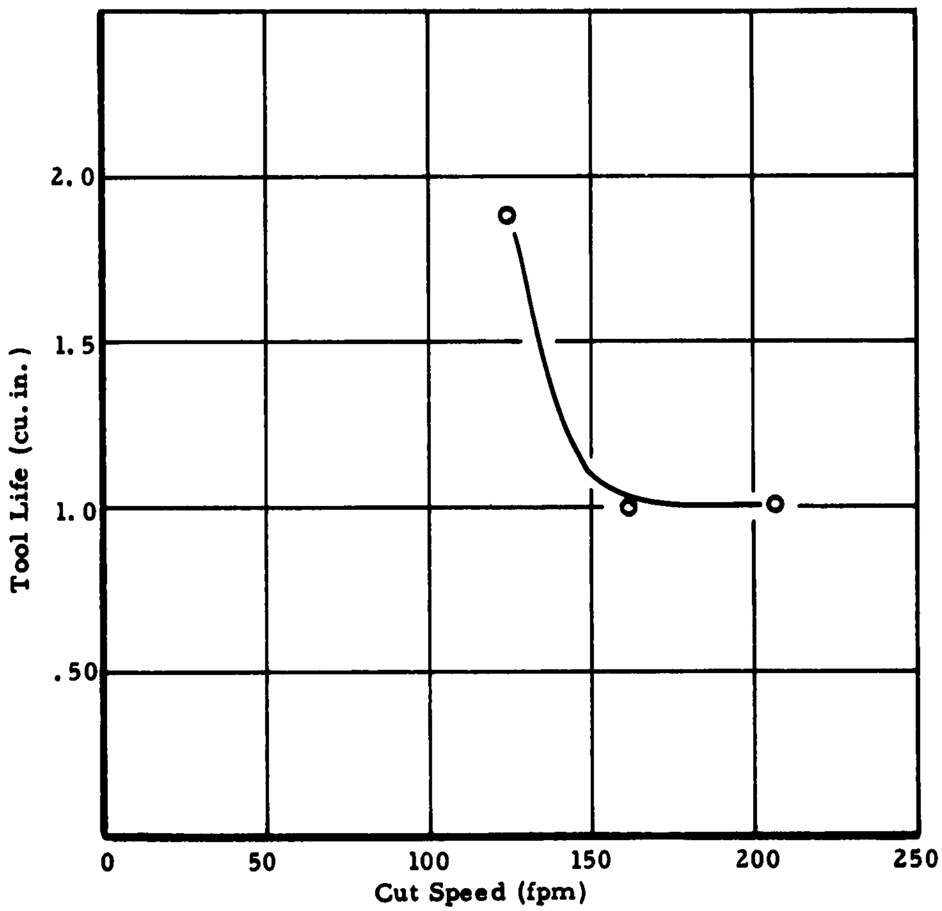
However, tool life decreased drastically as workpiece temperature was increased, as shown in Figure 148.

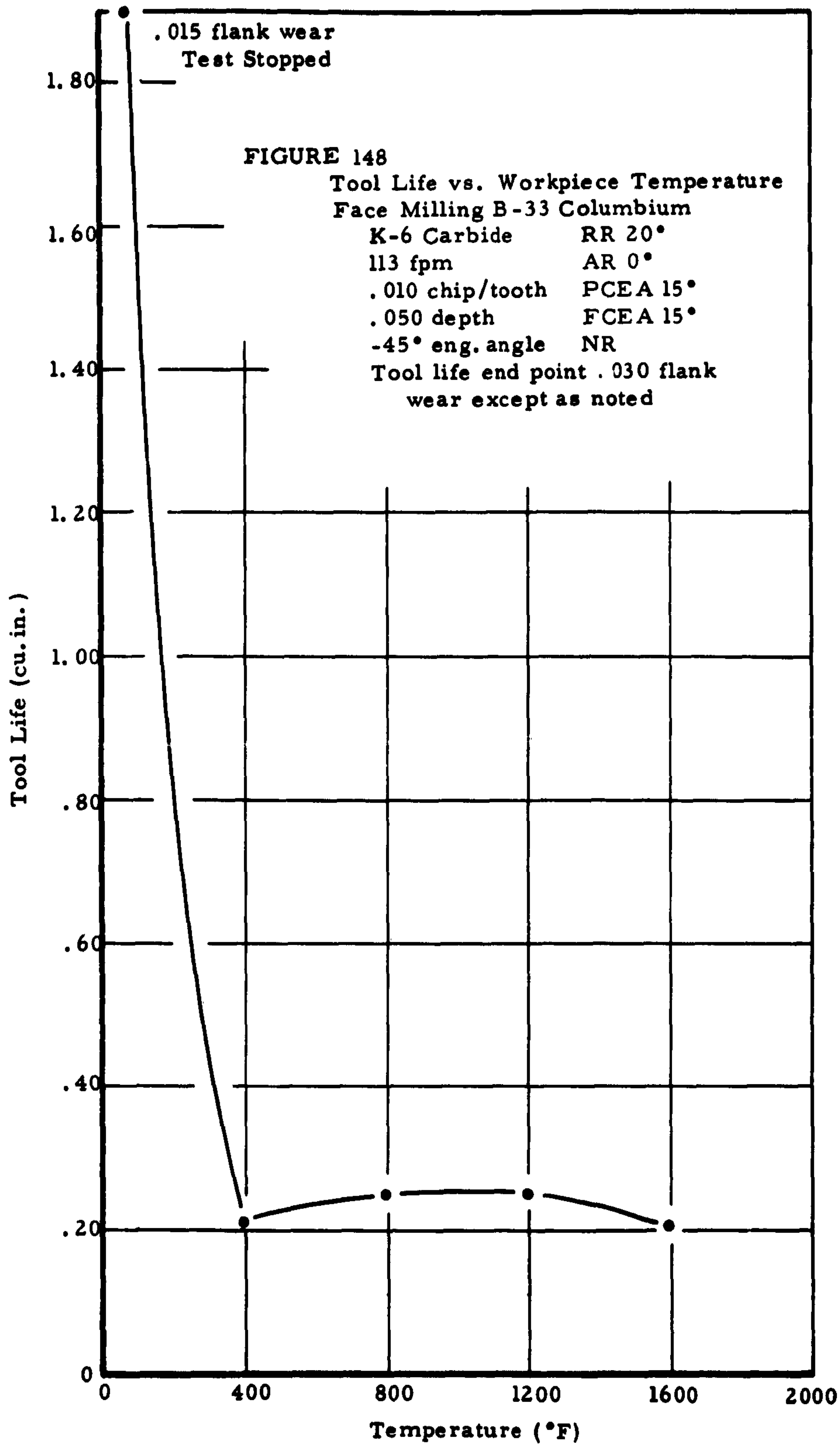
In addition to the welding wear expected when machining columbium, tool notching or cratering at the depth of cut was also found. It is felt that this notching is caused in part by stresses set up by uneven thermal expansion at the boundary between the hot interface area and the relatively cool tool surface not in the cut.

With the low feed rates necessary to mill some of these alloys, torch heating leaves much to be desired. The cooling time lag between arc application and actual metal cutting, as described on page 274, necessitates the heating of the metal far above the temperature desired at the cut. In some cases, the intense heat of the arc caused some surface melting, leaving a "crust" or solidified "puddle" to be machined off. This problem was partially overcome by heat soaking the workpiece before testing at high feed rates and then using the torch during machining only to maintain constant temperature. Further work is indicated in improving arc heating for these applications, such as the introduction of electrical resistance heaters into the work holding fixture to prevent excessive heat sinks.

FIGURE 147

Tool Life vs. Cut Speed
Face Milling B-33 Columbium
K-6 Carbide RR 20°
.050 depth AR 0°
.010 in/tooth PCEA 15°
-45° eng. angle FCEA 15°
Tool life end point .015 flank wear





.015 flank wear
Test Stopped
FIGURE 148
Tool Life vs. Workpiece Temperature
Face Milling B-33 Columbium
K-6 Carbide RR 20°
113 fpm AR 0°
.010 chip/tooth PCEA 15°
.050 depth FCEA 15°
-45° eng. angle NR
Tool life end point .030 flank wear except as noted
Tool Life (cu. in.)
1.80
1.60
1.40
1.20
1.00
.80
.60
.40
.20
0
0
400
800
1200
1600
2000
Temperature (°F)

TZM Molybdenum

The tool life cutting speed relationship for milling TZM molybdenum is given in Figure 149. Tool lives approximately equal were found at 200 fpm and at 669 fpm. At the high cutting speed, the induced temperature caused ductile chips to be formed, and an improved surface finish with less breakout resulted. The tool lives obtained agreed generally with those reported in Contract AF33(600)42349.

This high speed was used for elevated temperature testing because the high feed rates made ideal torch heating possible. However, tool life decreased with increased temperature, as shown in Figure 150. The usual accompanying cutting conditions are shown on the graphs.

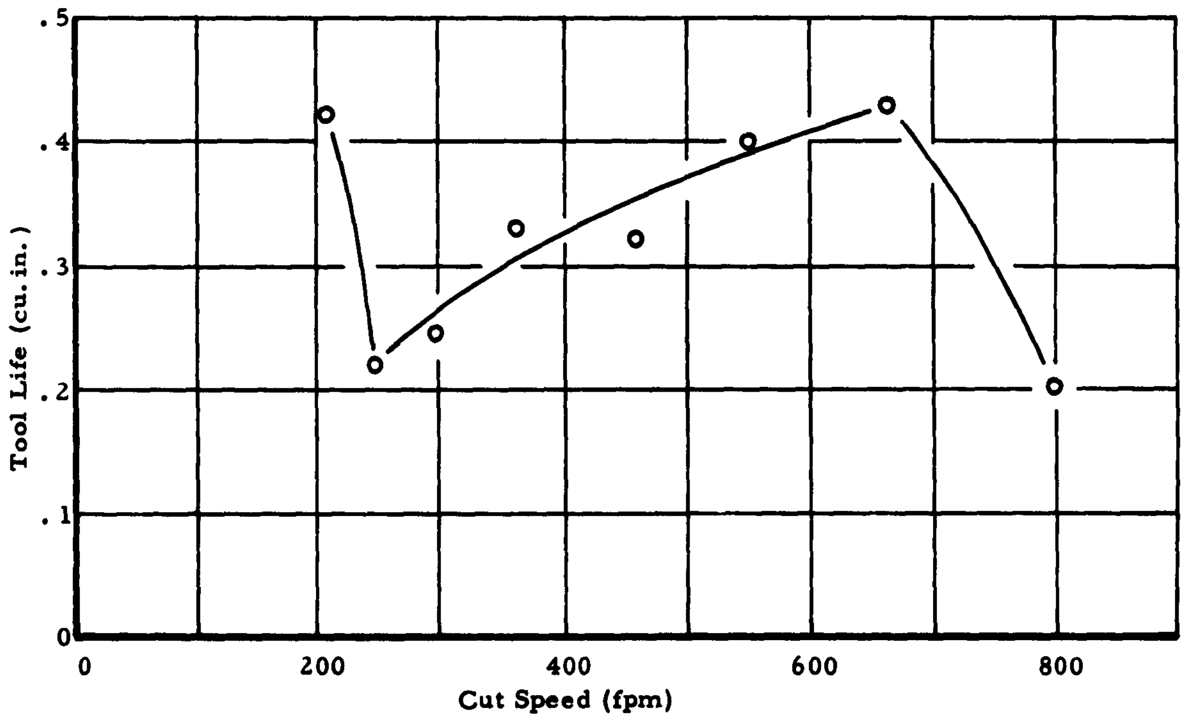
To evaluate the effect of the high cut speed at elevated temperature on tool life, several tests were run at 1200°F, but at lower speeds such as 400 and 200 fpm, with no tool life improvement resulting.

FIGURE 149

Tool Life vs. Cut Speed
Face Milling TZM Molybdenum

K-6 Carbide	RR 6°
.006 in/rev	AR 0°
.050 depth	PCEA 15°
-45° eng. angle	FCEA 15°

Tool life end point .015 flank wear



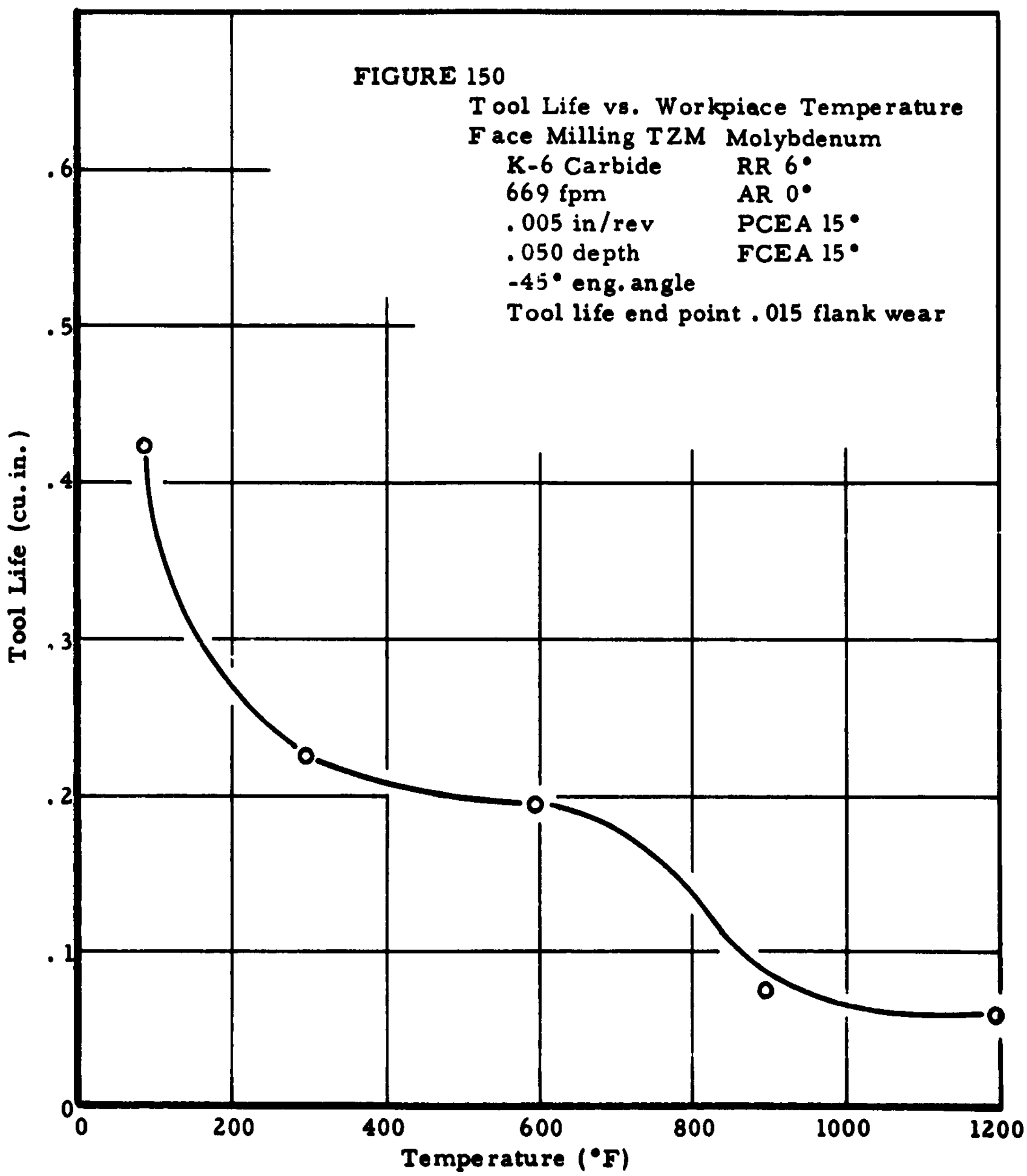


FIGURE 150
Tool Life vs. Workpiece Temperature
Face Milling TZM Molybdenum
K-6 Carbide
669 fpm
.005 in/rev
.050 depth
-45° eng. angle
RR 6°
AR 0°
PCEA 15°
FCEA 15°
Tool life end point .015 flank wear
Tool Life (cu. in.)
0
.1
.2
.3
.4
.5
.6
0
200
400
600
800
1000
1200
Temperature (°F)

Tungsten

Tungsten is probably the most difficult refractory metal to mill in the pressed and sintered form. Tool lives are extremely short, the metal is brittle at room temperature, and excessive breakout where the tool exits the workpiece is a common problem.

Dry, room temperature milling with K-6 grade carbide, 6° RR, 0° AR tools, 100-200 fpm, .010 feed/tooth and .060 depth of cut, yields tool lives on the order of 0.1 cubic inch of metal removed to .015 flank wear. Excessive breakout both when "on center" milling and -45° engagement angle milling is present. Powder instead of chips are formed under these conditions.

To induce ductile behavior in the tungsten, various elevated temperatures were tired. Significant tool life improvement was obtained at approximately 800°F, as is shown at the left in Figure 151. Specific cutting conditions are noted on the graph. Further temperature increase caused lower tool lives. At 800°F, ductile chips were formed, surface finish was improved somewhat, but breakout was only slightly reduced. Metcut likewise found 800°F to be an optimum hot machining temperature, as is also shown on the graph in Figure 151. However, they reported a larger tool life using a cutting fluid than they obtained at 800°F. Our investigation showed that 800°F yields the best tool life over all other conditions evaluated. Again, it appears that tungsten's variable mechanical properties become important in selecting optimum machining conditions.

The tool life cutting speed relationship found for tungsten at 800°F is given in Figure 152. Clearly, low cut speeds are better when machining tungsten.

The present arc heating method presented considerable trouble with the thermally sensitive pressed and sintered tungsten. Uneven heating caused workpiece cracking which ruined the tool as it passed through the crack. Upon release of vise pressure, the tungsten slab separated into several pieces.

On the Reduction of Breakout when Machining Tungsten

Our industrial survey shows that the "breakout" or crumbled edge on the exit side of tungsten workpieces was very common and was a serious problem. Our work described above confirms this result.

It was then decided to treat the amount of breakout as a function of tooth exit conditions, since ductile behavior during elevated temperature milling helped little in reducing breakout. The plan was to determine the optimum tooth exit angle, based on the known orientation of cutting forces, which would result in the least amount of breakout.

From work performed in this laboratory, it was known that the resultant force on a cutting edge in face milling acted at an average angle of approximately 35° to the direction of cutter motion. In the tests, where maximum breakout occurred, it was noticed that this resultant force acted in such a direction as to push directly against the exit edge and chip it away. See Figure 153A. Tests were then carried out to measure the amount of breakout at various tool exit angles, and the breakout - tool exit and breakout - engagement angle relationships obtained are given in Figure 154. It is seen that the least amount of breakout occurred where a high positive engagement angle was used, as in Figure 153B. In this case the resultant cutting force pushes longitudinally on the work at tooth exit and not out against the edge of the work. On the other hand, excessive breakout occurred at engagement angles which permitted the resultant cutting force to push against the edge of the work, such as between +10 and -20 angles. It is seen that doubling the feed per tooth increased breakout, but only slightly.

The reduction in breakout as engagement angle was varied from a highly positive angle (left) to only a slightly positive angle (right) may be seen in Figure 155.

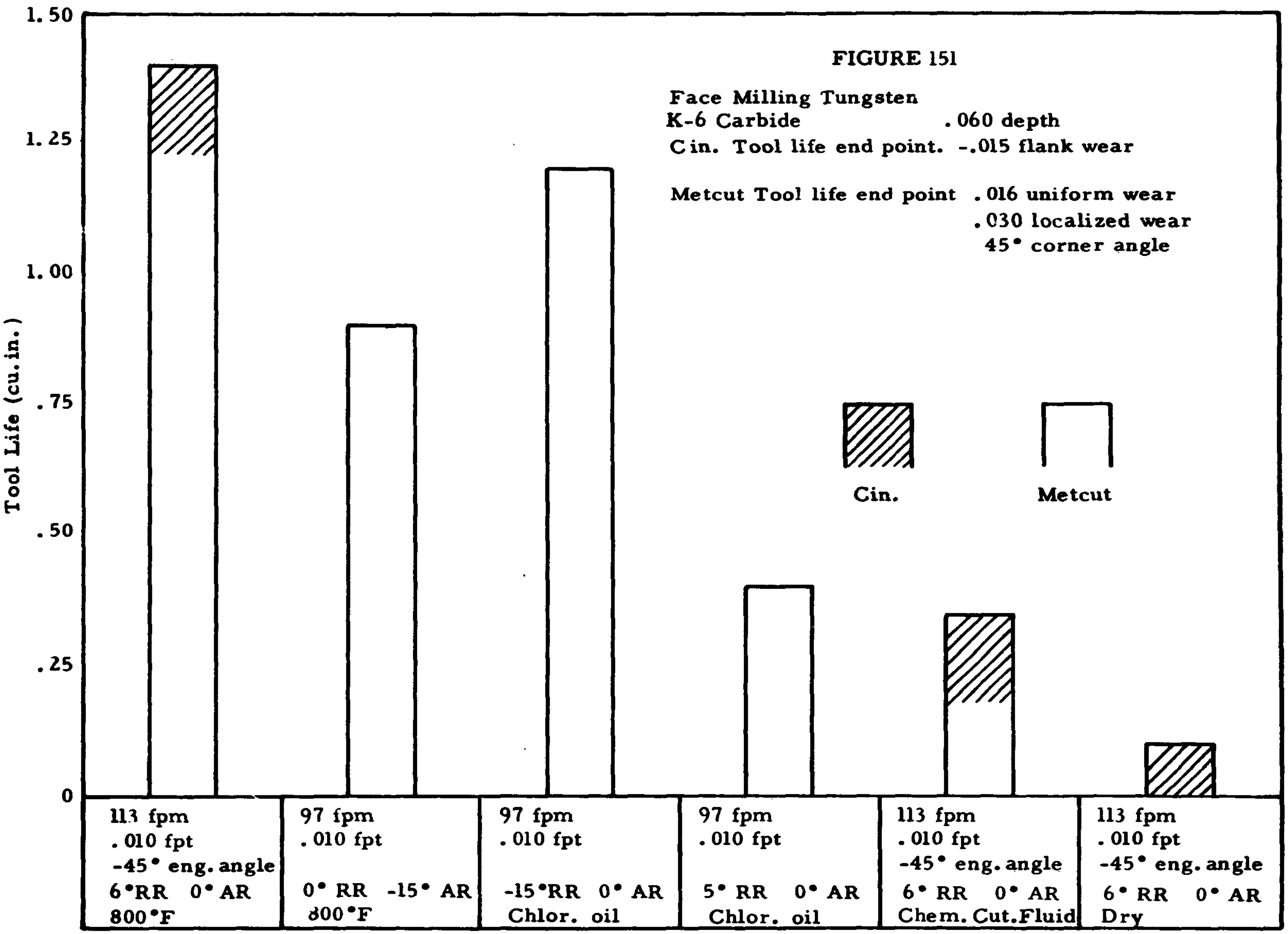


FIGURE 151
Face Milling Tungsten
K-6 Carbide .060 depth
C in. Tool life end point. -.015 flank wear
Metcut Tool life end point .016 uniform wear
.030 localized wear
45° corner angle
Cin.
Metcut
Tool Life (cu.in.)
1.50
1.25
1.00
.75
.50
.25
0
113 fpm .010 fpt -45° eng. angle 6°RR 0° AR 800°F
97 fpm .010 fpt 0° RR -15° AR 800°F
97 fpm .010 fpt -15°RR 0° AR Chlor. oil
97 fpm .010 fpt 5° RR 0° AR Chlor. oil
113 fpm .010 fpt -45° eng. angle 6° RR 0° AR Chem. Cut. Fluid
113 fpm .010 fpt -45° eng. angle 6° RR 0° AR Dry

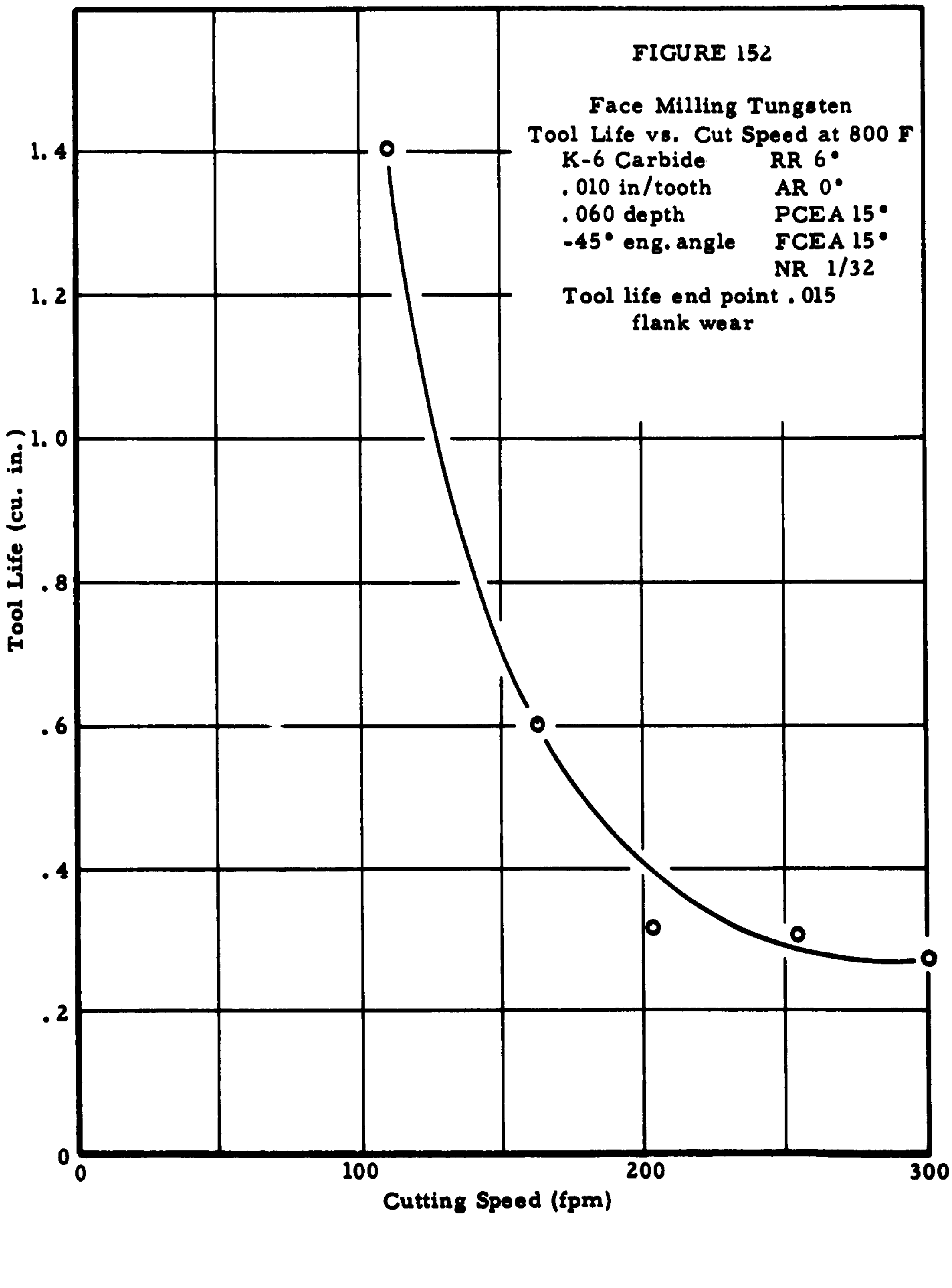


FIGURE 152
Face Milling Tungsten
Tool Life vs. Cut Speed at 800 F
K-6 Carbide
RR 6°
.010 in/tooth
AR 0°
.060 depth
PCEA 15°
-45° eng. angle
FCEA 15°
NR 1/32
Tool life end point .015 flank wear
Tool Life (cu. in.)
1.4
1.2
1.0
.8
.6
.4
.2
0
0
100
200
300
Cutting Speed (fpm)

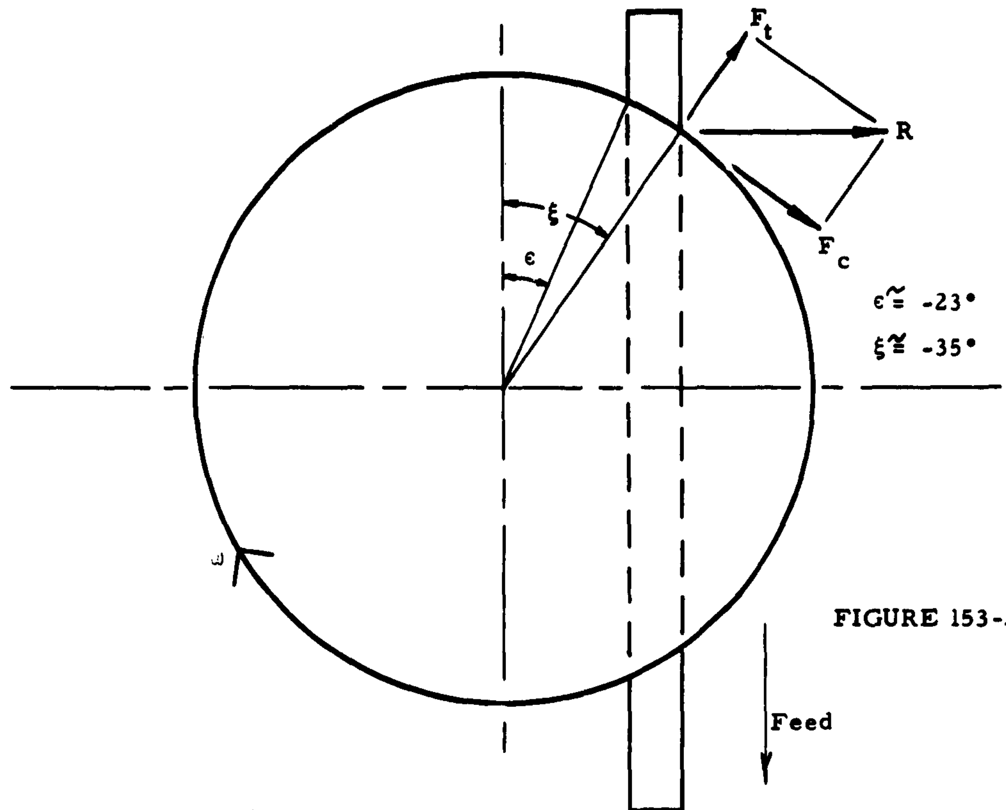


FIGURE 153-A

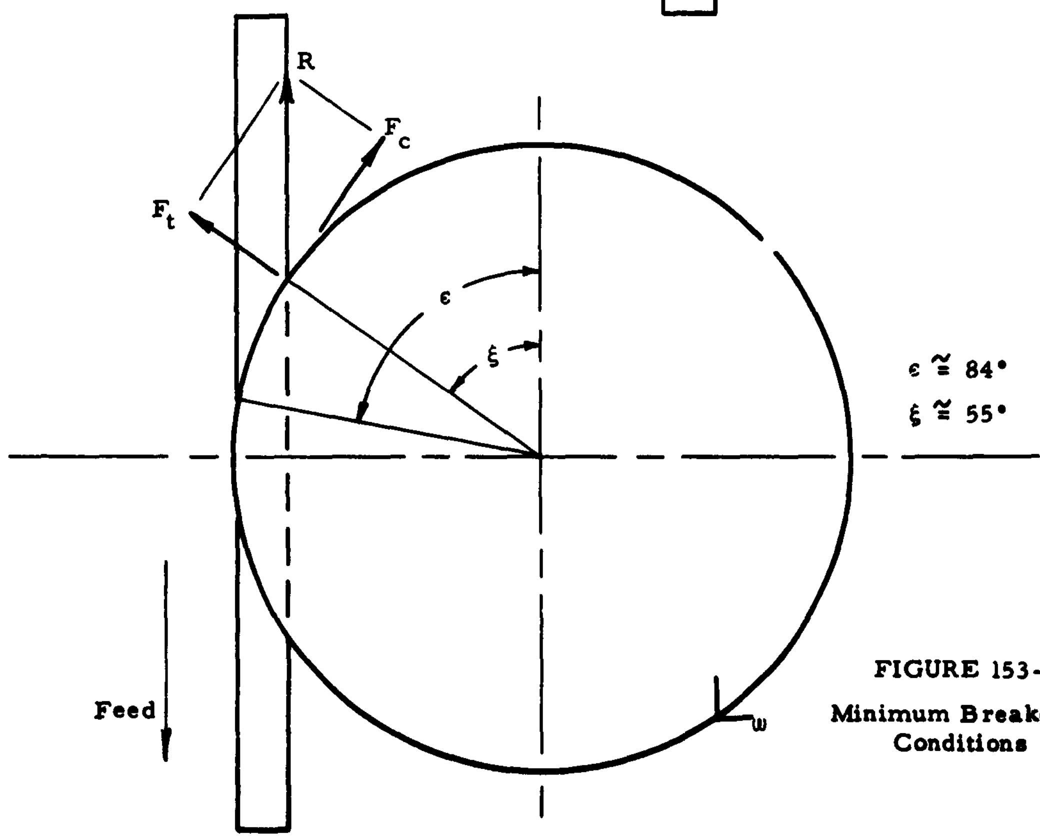


FIGURE 153-B

Minimum Breakout Conditions

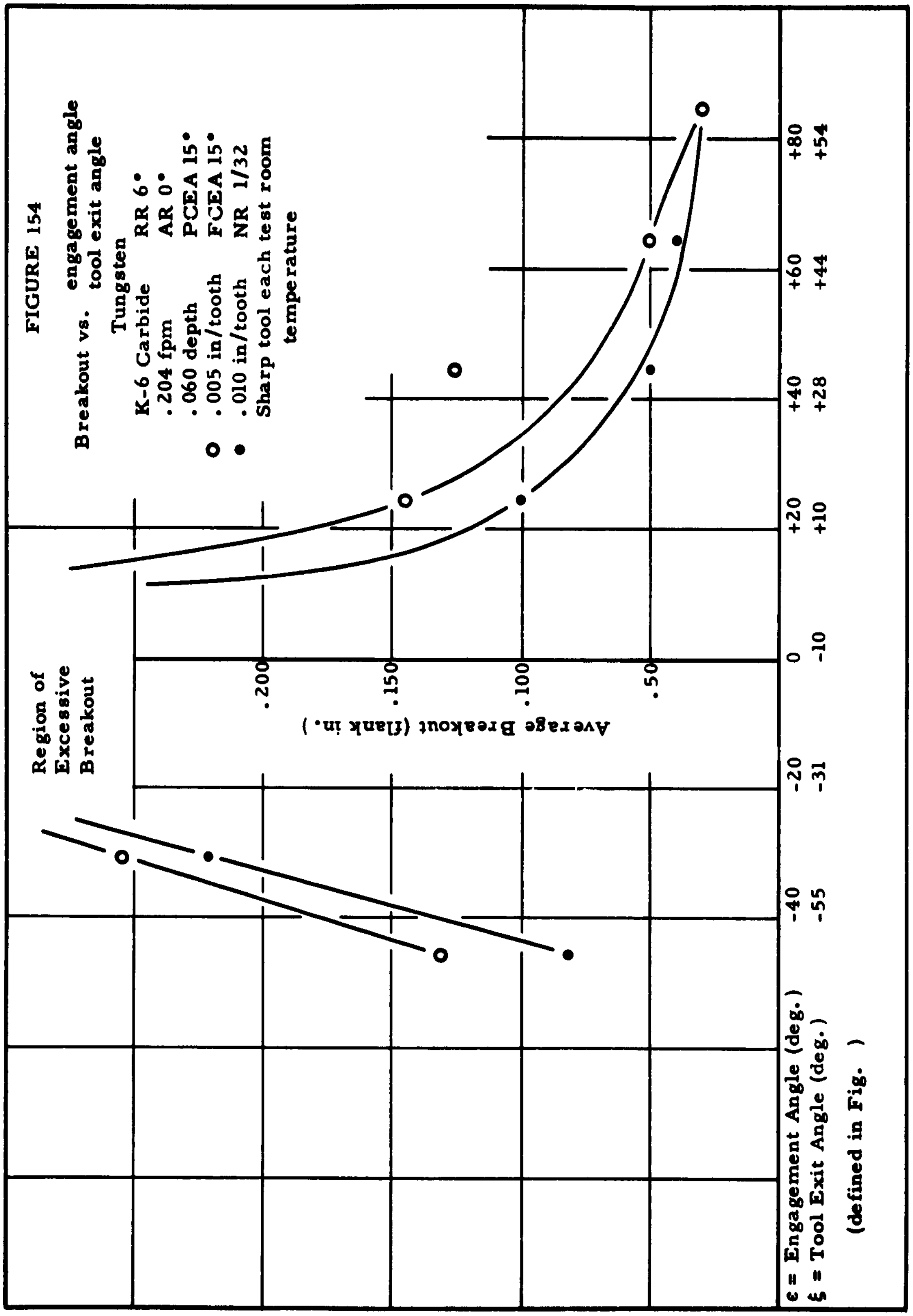


FIGURE 154

Breakout vs. engagement angle tool exit angle

MILLING TUNGSTEN
REDUCTION IN BREAKOUT WITH VARIATION IN ENGAGEMENT ANGLE

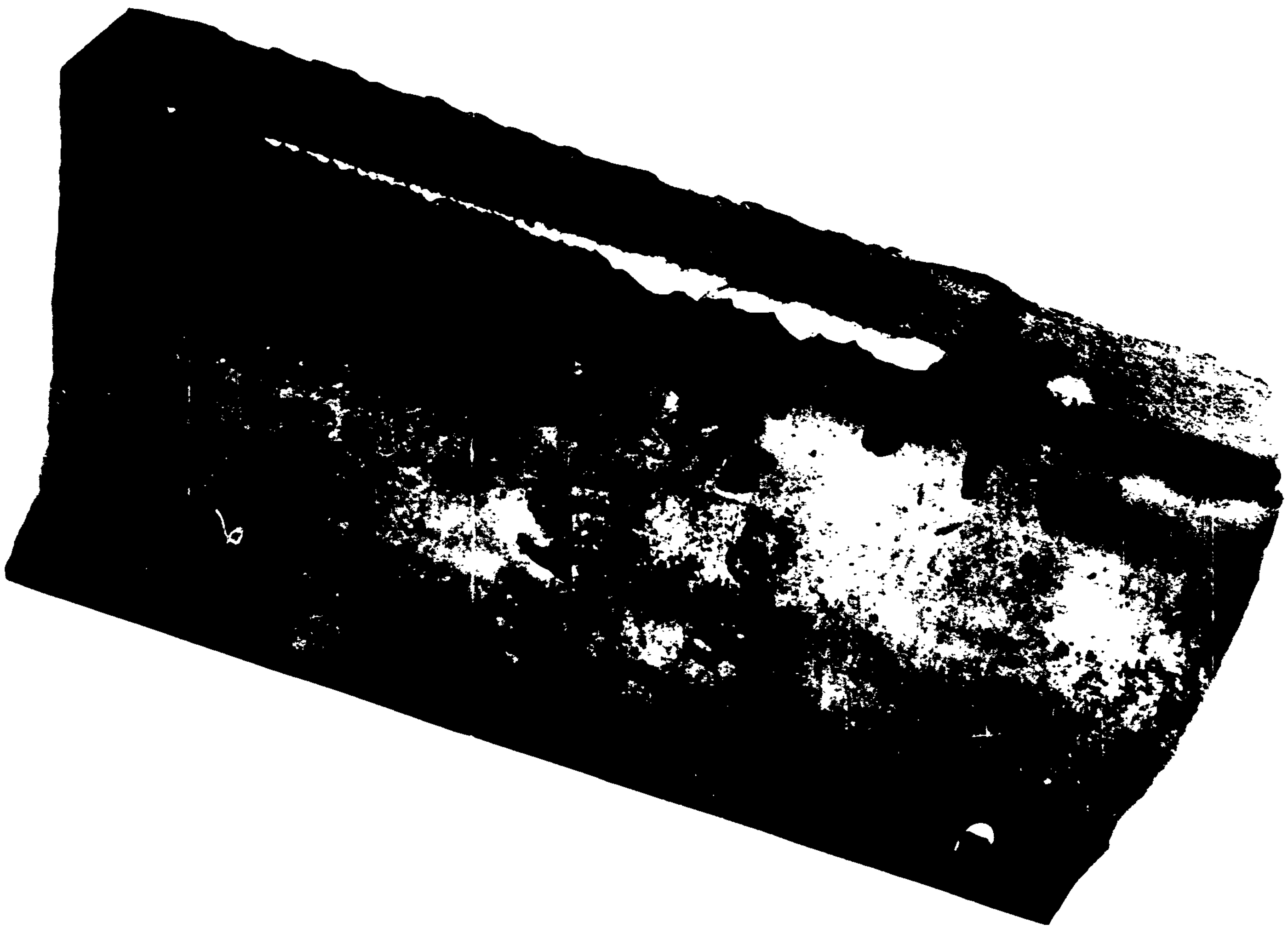


FIGURE 155

C 120 AV Titanium

The tool life cutting speed relationship for C 120 AV titanium is given in Figure 156. Specific cutting conditions are indicated. As can be seen, good tool life may be obtained in milling this titanium alloy at relatively high feeds per tooth. However, the -45° engagement angle is very important to minimize the chip-tool "welding" tendency exhibited by titanium. The low tool lives obtained using a -10° engagement angle at .010 feed/tooth offer verification, as can also be observed in Figure 156.

Dry, room temperature tool lives obtained were somewhat greater than those obtained by Metcut, who used not only similar cutting conditions but also a cutting fluid.

Further tool life improvement may be obtained by not permitting the tool to mill off the "corner" of the workpiece before it takes a full width of cut. This situation arises upon each new pass across the workpiece. Otherwise the advantage of a thin chip at tool exit using the -45° engagement angle is not realized. Quantitative evidence of tool life improvement is given in Figure 156, where the workpiece corner was pre-machined off and only full widths of cut were taken.

Since higher cut speeds offered reasonable tool lives, they were used to facilitate the better heating possible at higher feed rates. The relationship between tool life and workpiece temperature at conditions as recorded is given in Figure 157. Again, increased temperature enhances the welding tendency and reduces tool life. To cut down the relatively high self-induced temperature at this cut speed (464 fpm), lower cut speeds were tested, but to no avail.

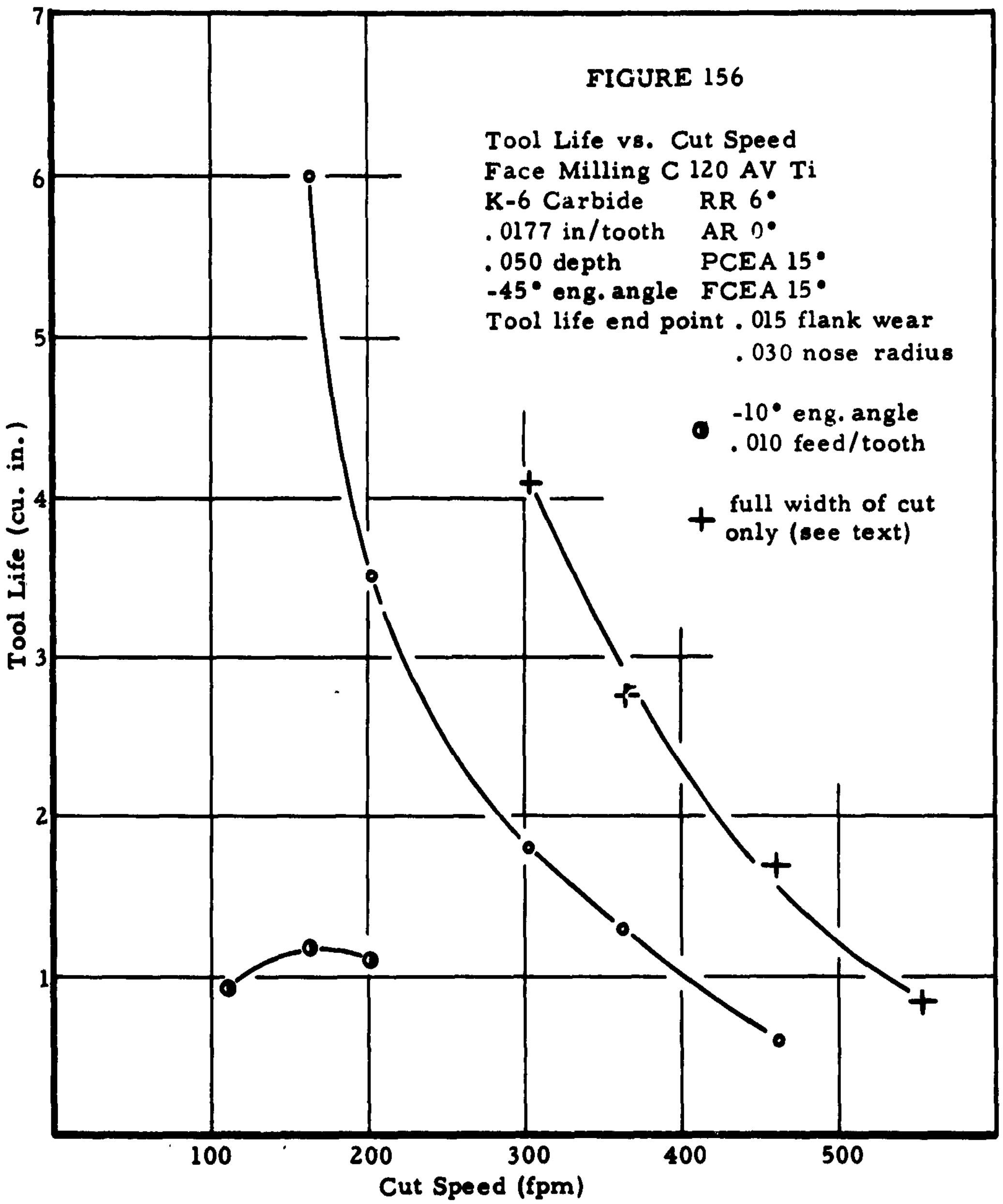


FIGURE 156
Tool Life vs. Cut Speed
Face Milling C 120 AV Ti
K-6 Carbide RR 6°
.0177 in/tooth AR 0°
.050 depth PCEA 15°
-45° eng. angle FCEA 15°
Tool life end point .015 flank wear
.030 nose radius
-10° eng. angle
.010 feed/tooth
full width of cut
only (see text)
Tool Life (cu. in.)
Cut Speed (fpm)
1
2
3
4
5
6
7
100
200
300
400
500

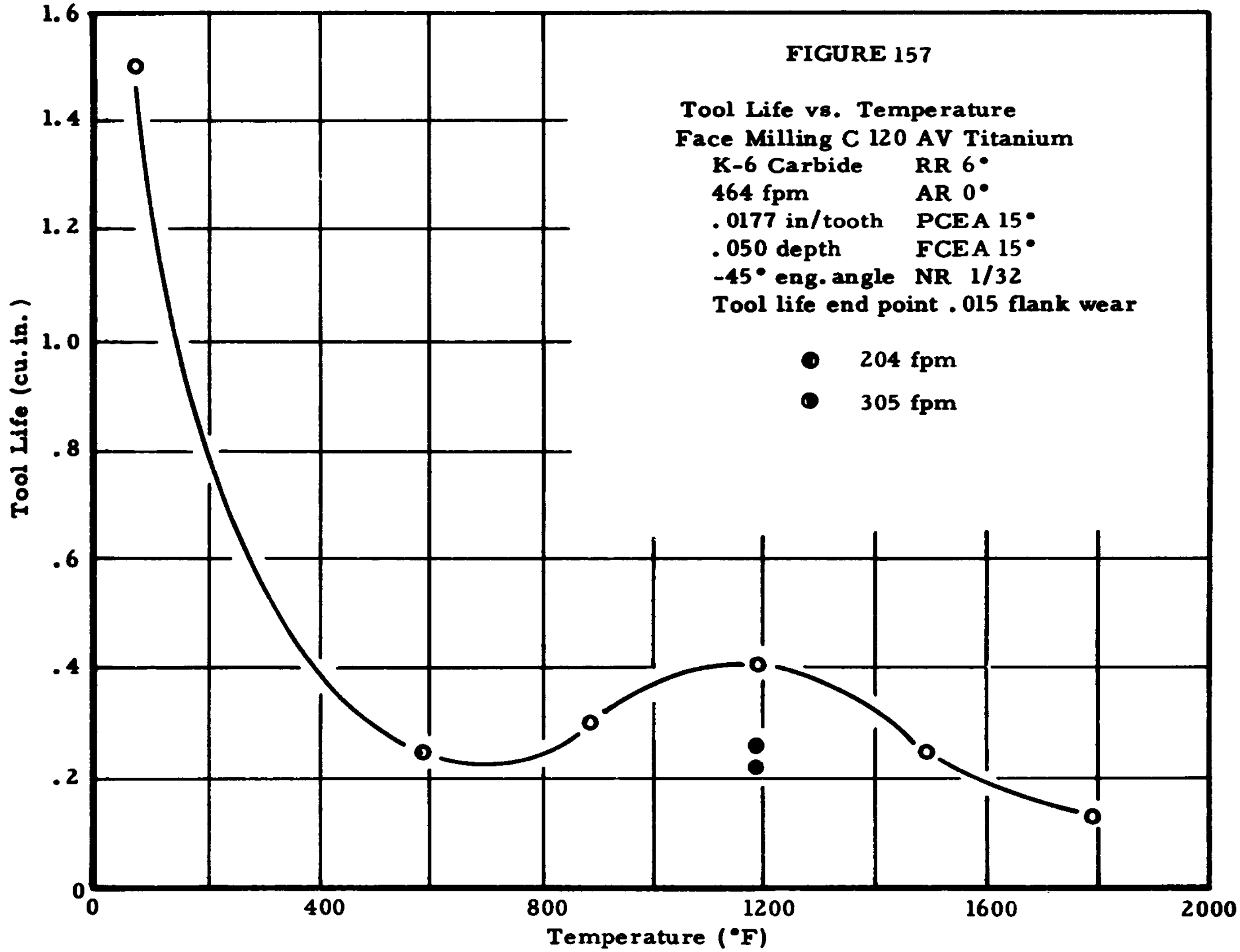


FIGURE 157
Tool Life vs. Temperature
Face Milling C 120 AV Titanium
K-6 Carbide RR 6°
464 fpm AR 0°
.0177 in/tooth PCEA 15°
.050 depth FCEA 15°
-45° eng. angle NR 1/32
Tool life end point .015 flank wear
204 fpm
305 fpm
Tool Life (cu. in.)
1.6
1.4
1.2
1.0
.8
.6
.4
.2
0
400
800
1200
1600
2000
Temperature (°F)

B-120 VCA Titanium

The rigidity of set-up necessary in machining titanium becomes very important in single tooth face milling relatively narrow workpieces of this alloy. Titanium's low modulus of elasticity (see Figure 133) causes substantial workpiece deflection during cutting and tool life is shortened. This is borne out by catastrophic failure of the cutting edge when the workpiece was allowed to overhang the holding fixture.

The tool life cutting speed relationship in Figure 158 was obtained after sufficient rigidity was assured. Other specific cutting conditions are recorded on the graph. Tool lives were very short compared to those obtained when milling the alpha-beta alloy (C 120 AV Ti).

Figure 159 gives the tool life workpiece temperature relationship in milling B 120 VCA Ti. It can be seen that some tool life improvement occurs around 900°F, but not as great as room temperature. The ductility increase at this temperature probably accounts for the tool life increase.

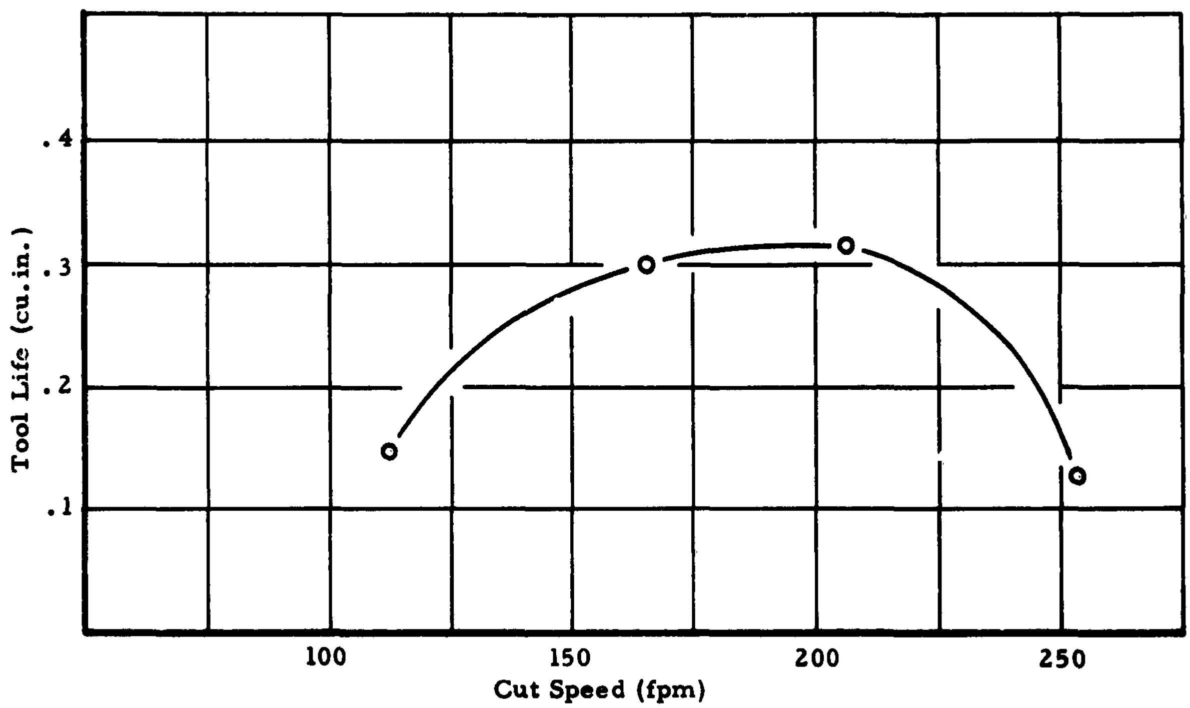
Further increase results in decreased tool life, with severe temperature welding causing rapid tool failure.

FIGURE 158

Tool Life vs. Cut Speed
Face Milling B 120 VCA Titanium

K-6 Carbide	RR 6°
.050 depth	AR 0°
.015 in/tooth	PCEA 15°
-45 eng. angle	FCEA 15°

Tool life end point =
.015 flank wear



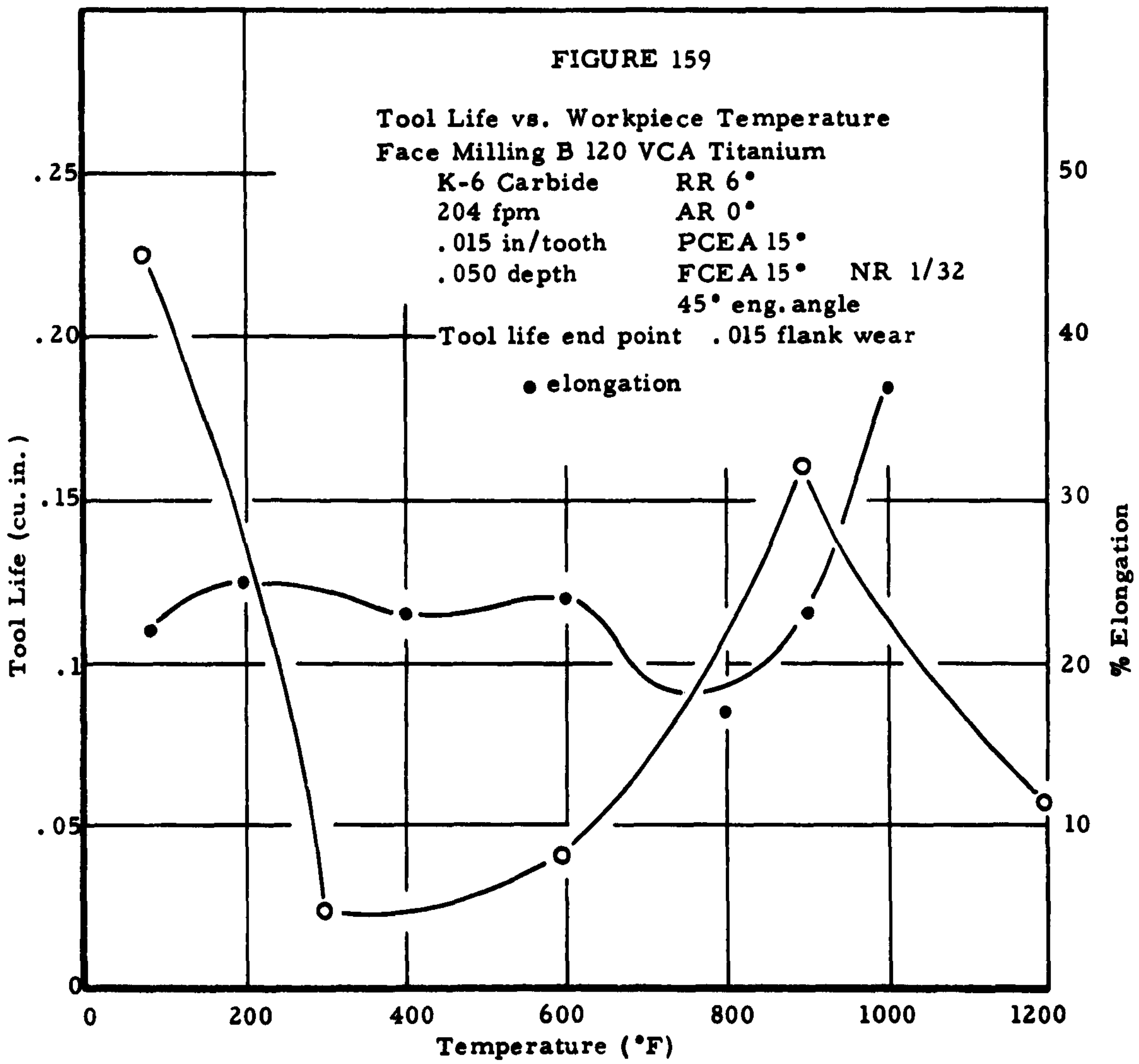


FIGURE 159
Tool Life vs. Workpiece Temperature
Face Milling B 120 VCA Titanium
K-6 Carbide
204 fpm
.015 in/tooth
.050 depth
RR 6°
AR 0°
PCEA 15°
FCEA 15°
NR 1/32
45° eng. angle
Tool life end point .015 flank wear
● elongation
Tool Life (cu. in.)
.25
.20
.15
.1
.05
0
% Elongation
50
40
30
20
10
0
200
400
600
800
1000
1200
Temperature (°F)

GENERAL CONCLUSIONS

It can be generally concluded that the elevated temperature machining of the alloys investigated can offer few advantages over conventional machining now in practice.

Slight tool life improvements in milling tungsten and 90 tantalum 10 W would not justify the expense of investing in a hot machining set-up for this purpose only. The reduction of breakout technique for machining tungsten should be of considerable aid to manufacturers of aerospace parts of that material.

Due to the high heat-resistant nature of the alloys investigated, the relatively low temperatures used in this evaluation were not sufficient to cause significant "metallurgical" damage to the workpiece. However, mention was made of the disadvantages of the inert arc heating method when low feeds are used. Uneven heating causes thermal cracking in some cases (tungsten, TZM molybdenum). Some surface effects from high heat concentration on low conducting rate materials (titanium) tend to lower tool life. However, surface effects are otherwise unimportant because the damaged surfaces are machined away and do not affect the finished part.

The argon loop bathing method proved very satisfactory in preventing oxidation of the workpieces in the temperature ranges investigated.

METALLURGICAL STUDIES

Introduction

It is important to understand the effects of elevated temperature machining on the metallurgy of the workpiece and to determine the distortion resulting from hot machining. This section gives results of studies carried out to evaluate the hardness, microstructure and distortion of hot machined parts. The four iron-base alloys, each of which at two hardness levels, the nickel base alloys, and the cobalt base alloy were examined for this study.

Metallurgical Procedure

Metallurgical samples were taken from a workpiece that had been hot face milled under the following conditions:

Iron base alloys:	Cutting speed - 256 fpm
	Feed - 0.0058 ipt
	Depth of cut - .125

The workpieces were heated to 1000°F with induction heating. One additional test was made to compare the metallurgical effects of R.F. induction heating versus R.F. resistance heating techniques.

The hot cutting conditions for the nickel and cobalt base alloys were as follows:

Rene' 41	155 fpm - .0054 ipt - 1/8 depth of cut workpiece temperature 1960°F
Inconel X	289 fpm - .0058 ipt - 1/8 depth of cut workpiece temperature 1450°F
Haynes Alloy No. 25	289 fpm - .0058 ipt - 1-1/8 depth of cut - workpiece temperature 800°F

Metallurgical samples were removed as is shown in Figure 160. Sample A was mounted in such a way that the microstructure of the workpiece could be examined from the hot machined surface to a point approximately 1/2 inch beneath the surface. This microstructure could be compared directly with that in Sample B which was taken from the bottom or unmachined portion of the workpiece. Samples A and B were mounted in the same mount, polished, etched and examined together to provide a direct comparison. A series of Knoop 300 gram microhardness indentations were made in a line normal to the hot machined surface on Sample A. The distance from the hot machined surface and the Rockwell C hardness value approximately equivalent to each of the Knoop hardness readings are given. Rockwell C readings were taken at 1/4 inch intervals across the depth of the entire block.

Results and Discussion

The photomicrographs and hardness readings taken from a Thermold J workpiece at 390 BHN and 570 BHN induction heated test specimens are shown in Figures 161, 162, 163, 164. In the case of the 390 BHN specimen, no evidence of tempering could be seen from either the photomicrograph or the hardness traverse. No evidence of grain coarsening was found. However, in the case of the 570 BHN sample it was obvious from both the photomicrograph and the hardness trace that the sample had been retempered at higher temperature during the machining process. No evidence of hot machining temperatures in the excess of grain coarsening temperatures was observed however.

Photomicrographs and hardness traverses of the induction heated test specimens of 17-4 MO stainless steel at 360 BHN and 380 BHN are shown in Figures 164, 165, and 166. In the case of the 360 BHN material, examination c the microhardness traverse in Figure 166 indicates that the hot machining operation has resulted in a decrease in hardness to a depth of approximately 3/8 inch. The microhardness values are somewhat erratic. The decrease in hardness could possibly be caused by overageing at the hot machining temperature. The difference in microstructure shown by Sample A and B in the photomicrograph may have been caused by a change in composition in the surface layer, resulting from reaction with furnace atmospheres during the heat treating cycle. A similar difference in microstructure was observed at the other end of the mounted specimen, except that the B sample showed the lack of grain boundary definition. In this case the end of the B sample had been exposed to the action of the furnace gases during heat treatment. In the case of the 380 BHN specimen, an examination of both microhardness and Rockwell C hardness traverses from these samples, indicate that a decrease in hardness to a depth of approximately 1 inch has resulted from the temperatures reached during hot machining. No changes in microstructure resulting from the temperatures reached during hot machining. No changes in microstructure resulting from the hot machining operation were detected.

Hot machining samples of induction heated specimens of 17-7 PH stainless steel at 360 BHN and 390 BHN are shown in Figures 167, 168 and 169. In the case of the 360 BHN, 17-7 PH specimen, there was some indication of a reduction in hardness adjacent to the hot machined end of the sample section. This may be a result of the heterogeneous microstructure rather than the hot machining operation. Hardness readings lower than those near the hot machined surface were obtained in the areas remote from this surface. No difference was detected in microstructure adjacent to the hot machined surface compared to that in the other portions of the sample. A similar relationship was also seen on the 390 BHN specimen.

The 4340 microstructures and hardness traverses taken from specimens at 390 BHN and 540 BHN are shown in Figures 170, 171 and 172. While the 390 BHN specimen showed only a slight decrease in hardness which may have resulted from tempering occurring during hot machining, the 540 BHN specimen showed that the piece had been retempered for approximately 2-1/2 inches beneath the hot machined surface. The decrease in hardness and change in microstructure, as shown by the photomicrographs showed that the temperature obtained during the hot machining process exceeded the original tempering temperature of the workpiece.

Because of the extreme change noticed with this alloy, it was decided that tests should be run with radio-frequency resistance heating to compare the change in microstructure resulting from the heating method. Consequently, two additional workpieces were prepared and machined using the radio-frequency resistance heating method. The photomicrographs and hardness traverses of these specimens at both 390 BHN and 540 BHN are shown in Figures 173, 174, and 175. On the 390 BHN specimen, no change in microhardness or microstructure was observed. In the case of the 540 BHN specimen, the hardness traverse showed that tempering had occurred down to approximately 1 inch beneath the hot machined surface. While the 540 BHN specimen was tempered to an unacceptable depth, which is not surprising due to the high temperature used in these tests, it should still be noted that the tempering was considerably less than with induction heating, showing that the possibility of using this type of heating on hard materials at a lower temperature without resulting damage to the workpiece.

Photomicrographs depicting the structure of Rene' 41 immediately beneath the hot machined surface at 100 X and 250 X are shown in Figure 176. The results of the hardness traverse over the .300 inch distance from the hot machined surface, converted from 300 g. Knoop, and the hardness traverse over the entire workpiece depth are shown in Figure 177.

A comparison of the microstructure on and adjacent to the hot machined surface with that of the unheated area fails to disclose any marked difference. There is some slight evidence from very close visual observation that the grain boundaries in or near the hot machined surface tend to be somewhat more discontinuous than those in the unheated portion of the sample. The temperatures obtained prior to and during the hot machining process would also be expected to redissolve some of the gamma prime precipitate. Were this to happen to any large degree a reduction in hardness would result. The absence of such hardness change indicates that either the time at temperature was so short that sufficient re-solution failed to occur, or if re-solution did occur the gamma prime microconstituent was re-precipitated.

The scatter in microhardness values shown in Figure 177 is caused by the intersection or lack of intersection of the hardness indentation with the boundaries of the relatively large grains composing the microstructures of the material. No attempt was made to select grain boundary free areas in which to make these hardness indentations.

Figure 178 shows the microstructure of Inconel X as examined near the hot machined surface at 100 X and 250 X. Figure 179 graphically illustrates the hardness values obtained at different distances beneath the hot machined surface. A comparison of the microstructure at or near the hot machined surface with that of unheated Inconel X sample, the unheated area, shows that somewhat more changes occurred in the microstructure of this material than in the Rene' 41 sample. Although not shown in the photomicrographs, under other conditions of etching, two distinct layers were observed. A light etching layer extended from the hot machined surface to a depth of .015.

We believe that the precipitated microconstituent in this area has been re-dissolved, and the solution partially auto-aged so that about the same hardness level was obtained in the surface layers. Blending into this area and extending to about .050" below the hot machined surface is a layer of dark etching, softened material which probably resulted from overageing.

The workpiece from which this specimen was taken, was machined with a four toothed cutter as were the other workpieces. The small number of teeth required a low table feed rate. Were a production cutter with a greater number of teeth to be used, the feed rate would be increased. This would decrease the length of time the workpiece is heated and would increase the temperature gradient. These two factors will decrease the extent and the severity of the metallurgical change.

The results of the study on Haynes Alloy No. 25 are shown in Figures 180 and 181 which show the microstructure beneath the hot machined surface at 100 X and 250 X and the hardness traverses respectively.

This specimen showed no evidence of a metallurgical change resulting from the heating of the workpiece because of the low workpiece temperature. The distorted grains and increased hardness at the surface give evidence of the cold working during machining. While no comparison was made, it is expected that the work hardening from hot machining is not as severe as that which would occur with conventional machining, because of the lower cutting forces and the possibility of stress relief from the 750°F workpiece temperature.

Workpiece Distortion

Dimensional changes of the workpiece due to uneven heating and cooling, can result in considerable distortion of the workpiece under adverse conditions in hot machining. This problem can be alleviated in many cases by correct heating methods, but the basic need is for techniques which will allow good concentration of heat to be obtained. Workpiece distortion was measured by making a single cut in the hot workpiece with parallel faces and then measuring the resulting bow with a dial indicator. Results of these tests are shown in Figures 182 and 183. Note should be taken of the reduction in distortion obtained when R.F. resistance heating was used. See the right side of Figure 182. The distortion was approximately 1/3 of that obtained when induction heating was used due to the much better localization of heat achieved by R.F. resistance heating technique.

SAMPLES FOR MICROSTRUCTURE AND HARDNESS EXAMINATION OF HOT MACHINED TEST WORK PIECES

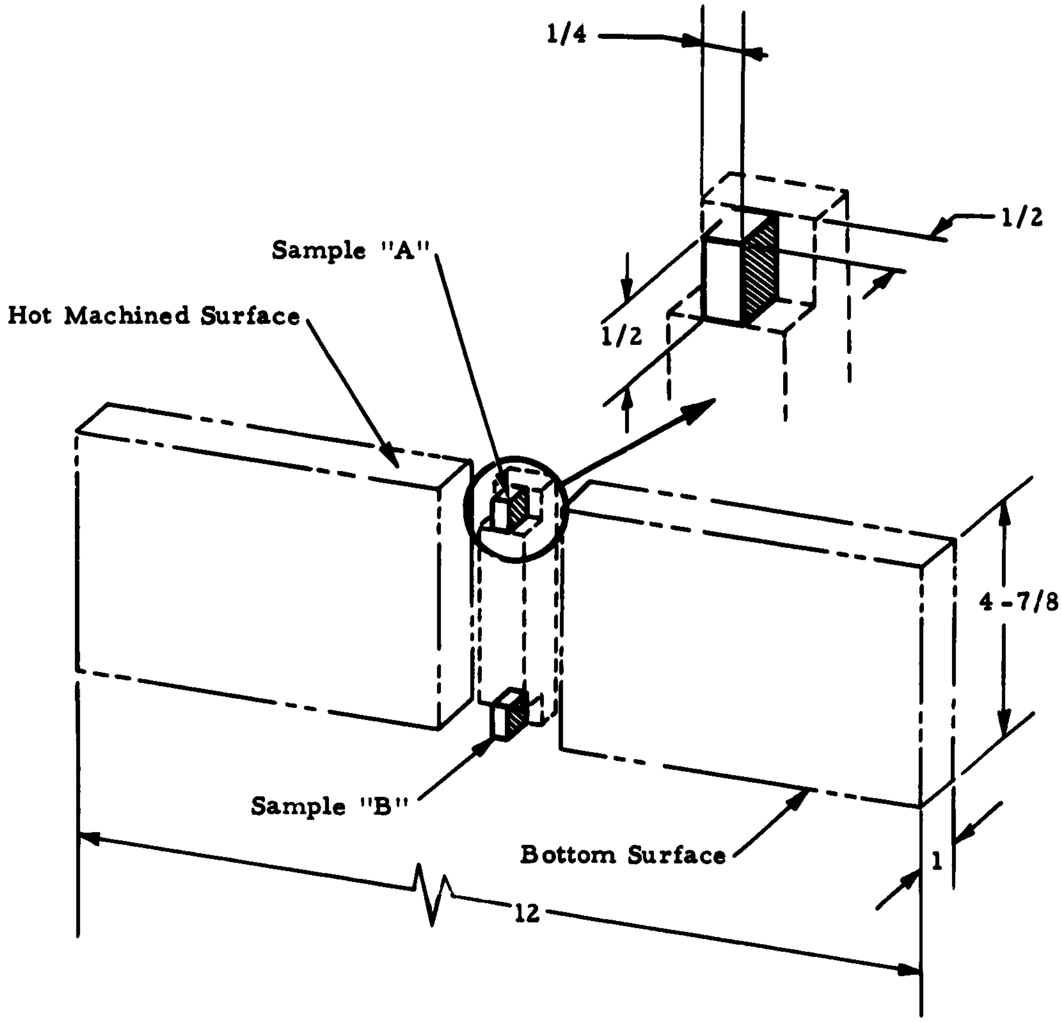


FIGURE 160

MICROSTRUCTURE AND HARDNESS EXAMINATION OF HOT MACHINED TEST SAMPLES

Material "Thermold J" 390 BHN
Heat Treatment - Preheated to 1200°F, Air Quenched from 1875°F, Double Tempered at 1100°F

Vilella's Reagent

Sample A *41 Rc. | Sample B *41 Rc.

Photomicrograph (250X)

Sample A *41 Rc. | Sample B *41 Rc.

Photomicrograph (1000X)

Upper surface of sample A is hot machined surface.
Upper surface of sample B is approximately 4-1/4 in. under upper surface of sample A.

*Hardness taken 0.006 in. below upper surface shown in photomicrographs (converted from 500 gram Knoop).

FIGURE 161

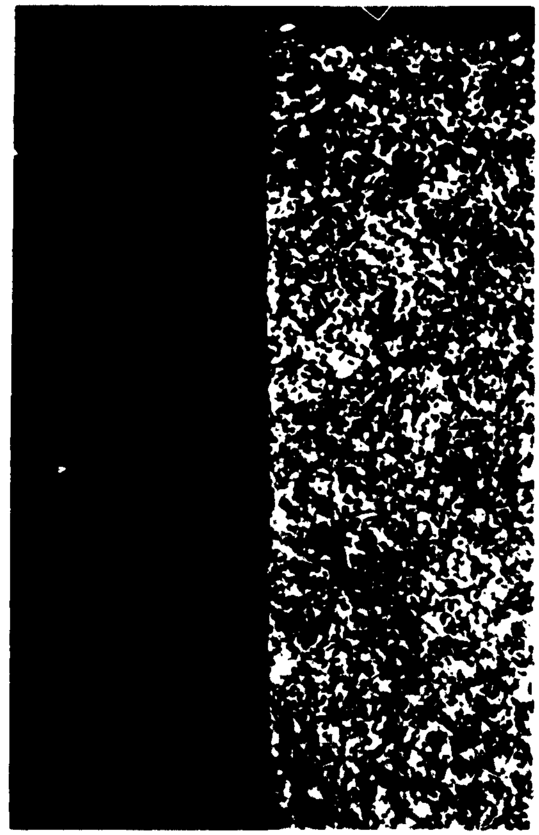
MICROSTRUCTURE AND HARDNESS EXAMINATION OF HOT MACHINED TEST SAMPLES

Material "Thermold J" 570 BHN
Heat Treatment - Preheated to 1200°F, Air Quenched from 1800°F
Double Tempered at 800°F

Vilella's Reagent

Sample A ***54 Rc.** **Sample B** ***58-1/2 Rc.**

Photomicrograph (250X)



Sample A ***54 Rc.** **Sample B** ***58-1/2 Rc.**

Photomicrograph (1000X)

Upper surface of sample A is hot machined surface.
Upper surface of sample B is approximately 4-1/4 in. under upper surface of sample A.

***Hardness taken 0.006 in. below upper surface shown in photomicrographs (converted from 500 gram Knoop).**

FIGURE 162

EFFECT OF HOT MACHINING ON THE HARDNESS OF THERMOLD J
HARDNESS vs DISTANCE FROM HOT MACHINED SURFACE
(INDUCTION HEATED)

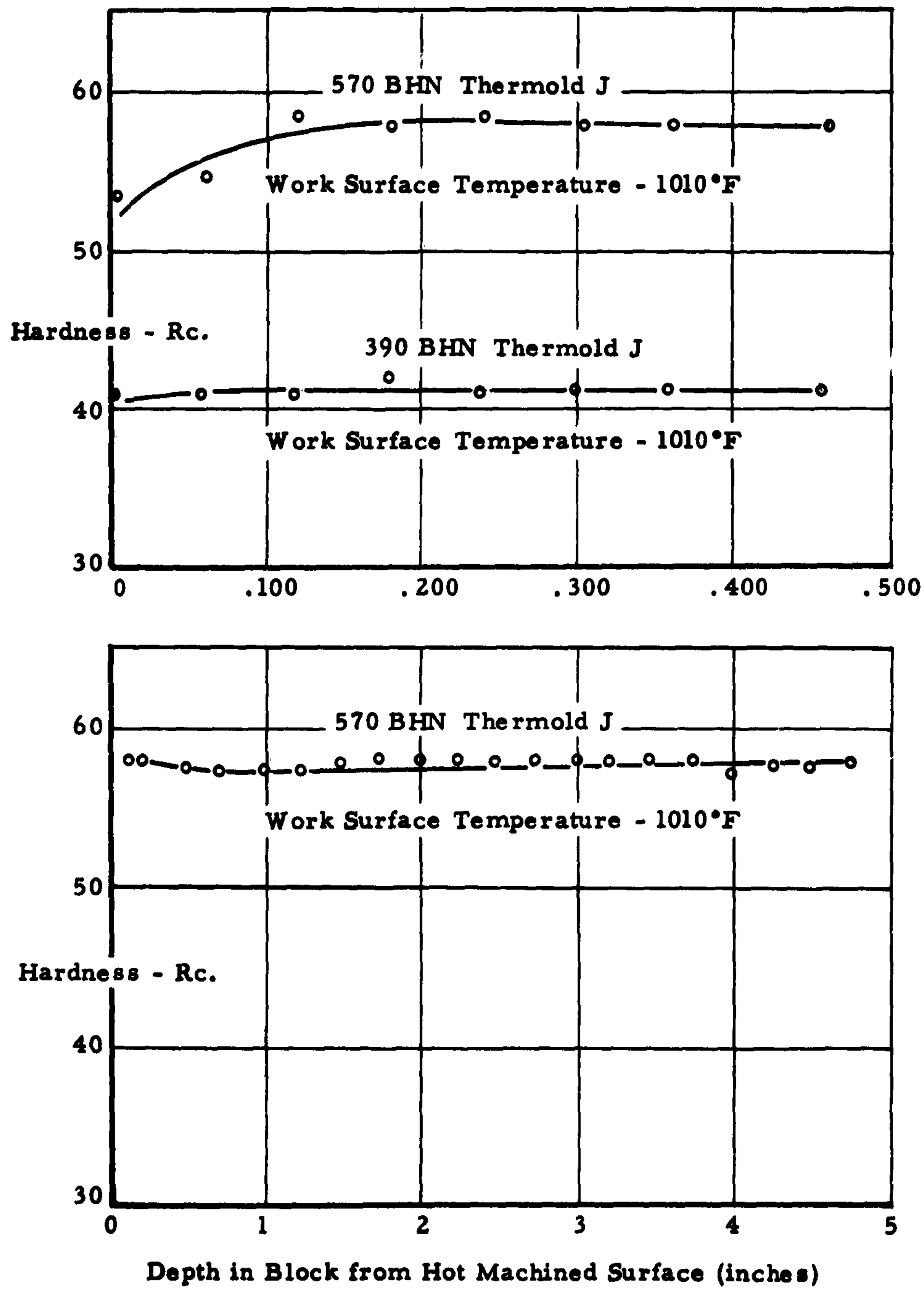


FIGURE 163

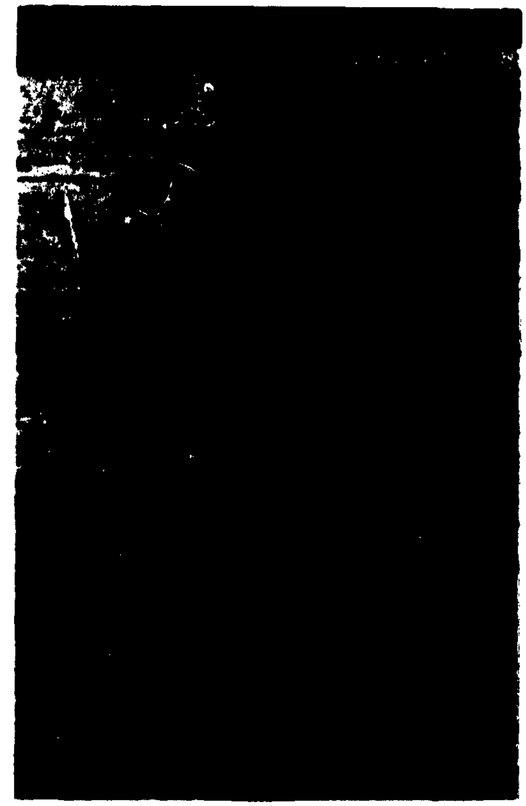
MICROSTRUCTURE AND HARDNESS EXAMINATION OF HOT MACHINED TEST SAMPLES

Material 17-4 MO, 360 BHN

Etch - Alcohol, HCl + HNO_3, $FeCl_3$

Sample A *41 Rc. | Sample B *43-1/2 Rc.

Photomicrograph (250X)



Sample A *41 Rc. | Sample B *43-1/2 Rc.

Photomicrograph (1000X)

Upper surface of sample A is hot machined surface.
Upper surface of sample B is approximately 4-1/4 in. under upper surface of sample A.

*Hardness taken 0.006 in. below upper surface shown in photomicrographs (converted from 500 gram Knoop).

FIGURE 164

MICROSTRUCTURE AND HARDNESS EXAMINATION OF HOT MACHINED TEST SAMPLES

Material 17-4 MO, 380 BHN

Etch - Alcohol, HCl + HNO_3, $FeCl_3$

Sample A	Sample B	Sample A	Sample B
*38 Rc.	*42 Rc.	*38 Rc.	*42 Rc.

Photomicrograph (250X)   Photomicrograph (1000X)

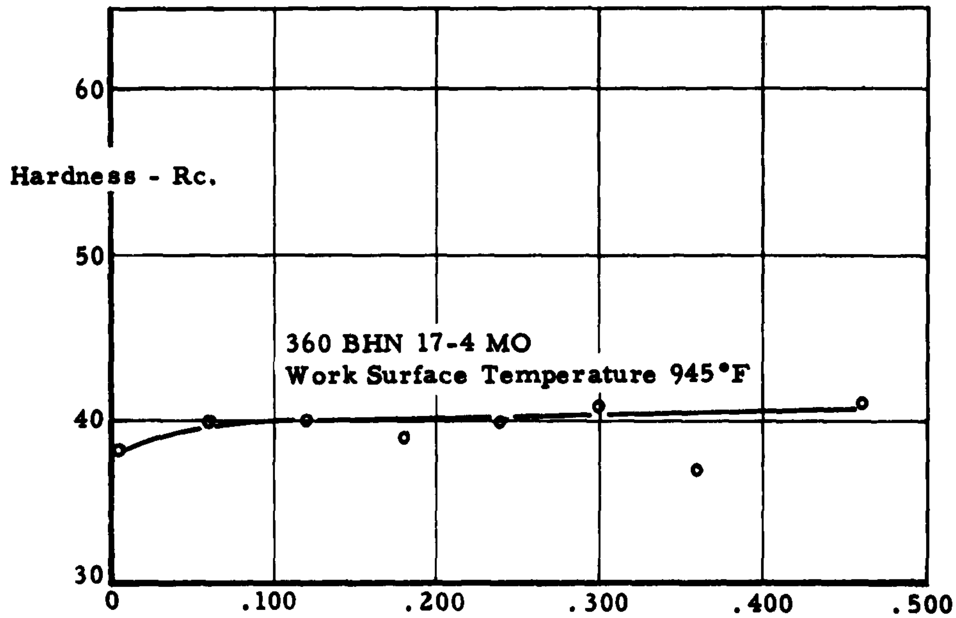
Upper surface of sample A is hot machined surface.
Upper surface of sample B is approximately 4-1/4 in. under upper surface of sample A.

*Hardness taken 0.006 in. below upper surface shown in photomicrographs (converted from 500 gram Knoop).

FIGURE 165

EFFECT OF HOT MACHINING ON THE HARDNESS OF 17-4 MO

HARDNESS vs DISTANCE FROM HOT MACHINED SURFACE (INDUCTION HEATED)



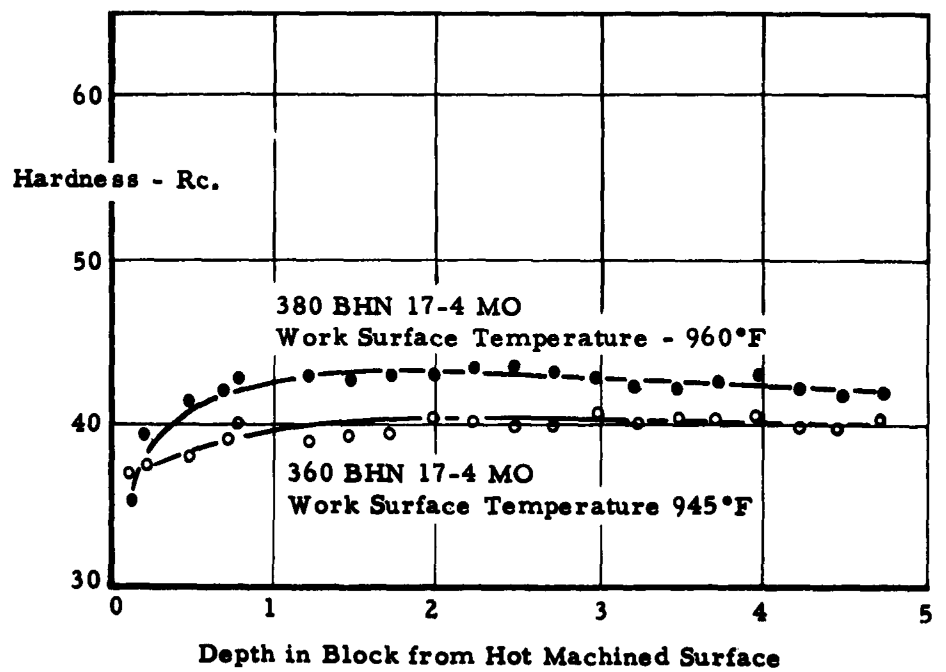


FIGURE 166

MICROSTRUCTURE AND HARDNESS EXAMINATION OF HOT MACHINED TEST SAMPLES

Material 17-7 PH, 360 BHN

Etch - Alcohol, HNO_3 + HCl, $FeCl_3$

Sample A	Sample B	Sample A	Sample B
*37 Rc.	*41 Rc.	*37 Rc.	*41 Rc.

Photomicrograph (250X) Photomicrograph (1000X)

Upper surface of sample A is hot machined surface.
Upper surface of sample B is approximately 4-1/4 in. under upper surface of sample A.

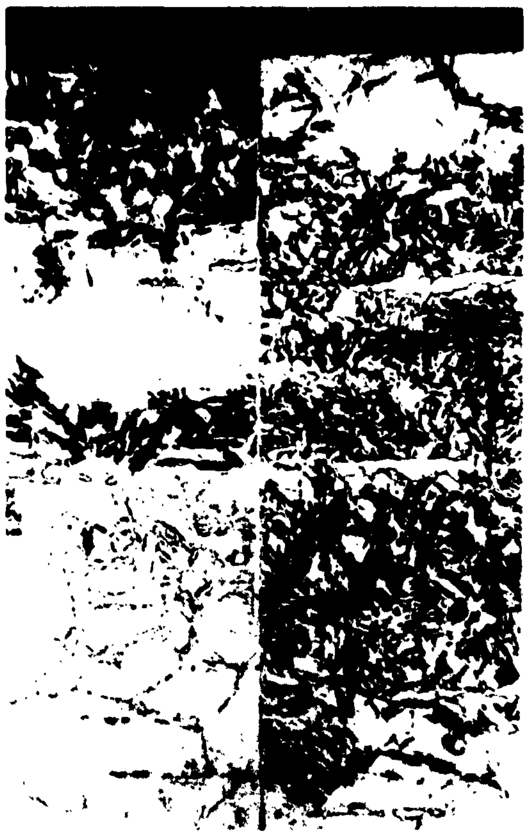
*Hardness taken 0.006 in. below upper surface shown in photomicrographs (converted from 500 gram Knoop).

FIGURE 167

MICROSTRUCTURE AND HARDNESS EXAMINATION OF HOT MACHINED TEST SAMPLES

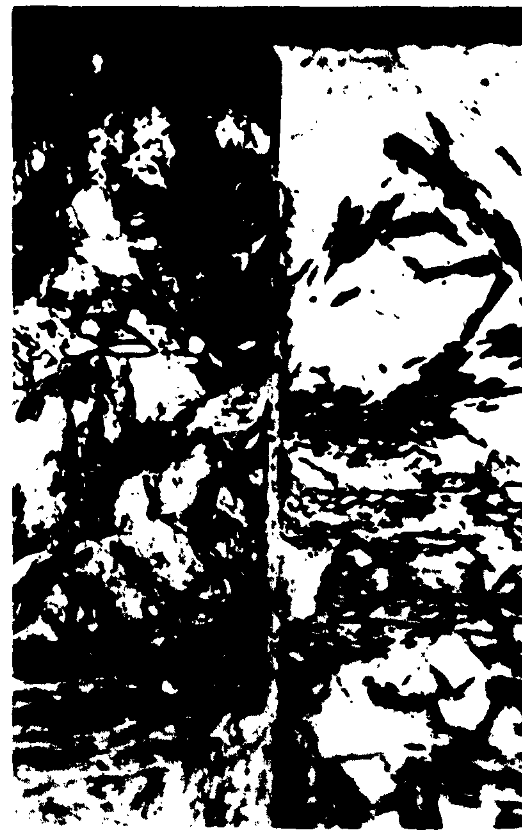
Material 17-7 PH, 390 BHN

Etch - Alcohol, HCl + HNO_3, $FeCl_3$



Sample A — *36 Rc. Sample B — *42-1/2 Rc.

Photomicrograph (250X)



Sample A — *36 Rc. Sample B — *42-1/2 Rc.

Photomicrograph (1000X)

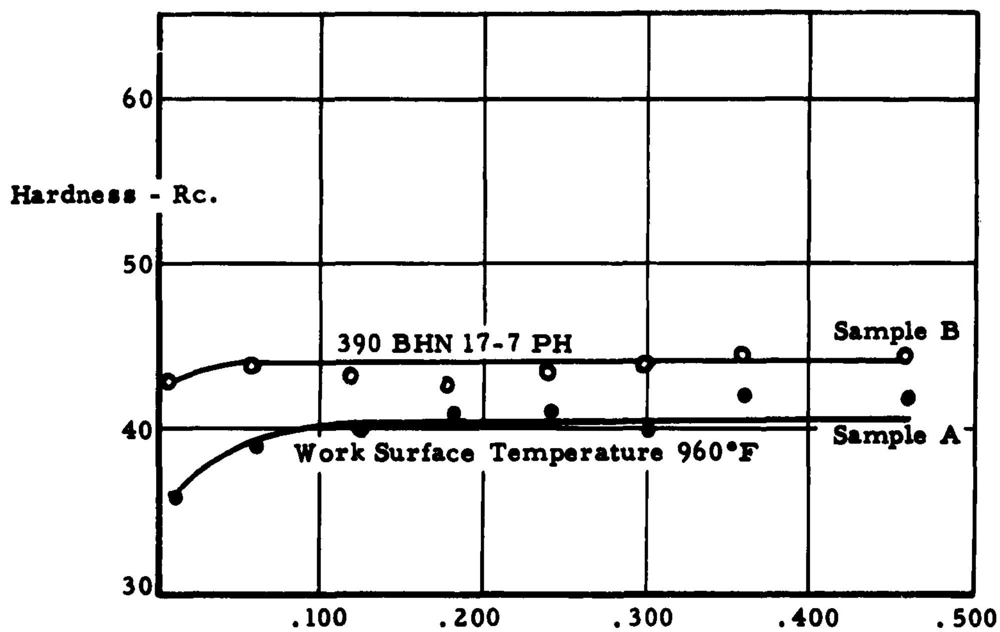
Upper surface of sample "A" is hot machined surface.
Upper surface of sample "B" is approximately 4-1/4 in. under upper surface of sample A.

*Hardness taken 0.006 in. below upper surface shown in photomicrographs (converted from 500 gram Knoop).

FIGURE 168

EFFECT OF HOT MACHINING ON THE HARDNESS OF 17-7 PH

HARDNESS vs DISTANCE FROM HOT MACHINED SURFACE (INDUCTION HEATED)



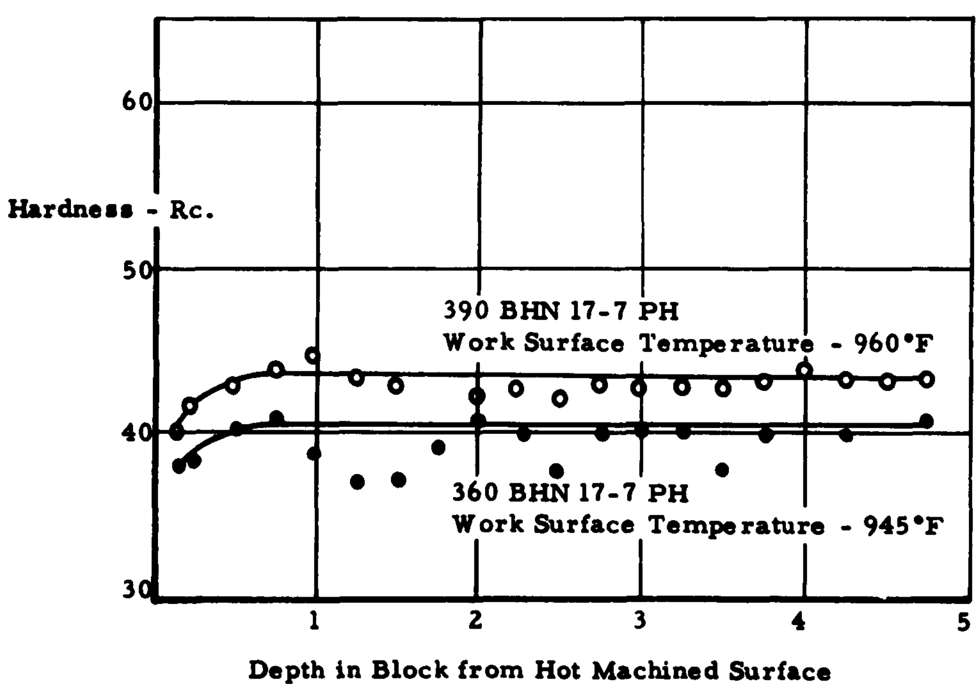
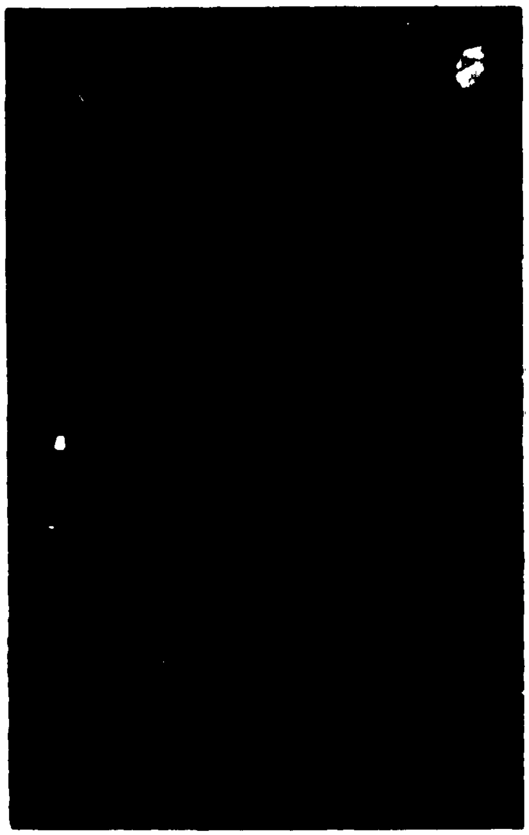


FIGURE 169

MICROSTRUCTURE AND HARDNESS EXAMINATION OF HOT MACHINED TEST SAMPLES

Material 4340, 390 BHN, Induction Heated
Heat Treatment - Oil Quenched and Tempered

2% Nital Etch



Sample A
*36-1/2 Rc.

Sample B
*42-1/2 Rc.

Photomicrograph (250X)

Sample A
*36-1/2 Rc.

Sample B
*42-1/2 Rc.

Photomicrograph (1000X)

Upper surface of sample "A" is hot machined surface.
Upper surface of sample "B" is approximately 4-1/4 in. under upper surface of sample "A".

*Hardness taken 0.006 in. below upper surface shown in photomicrographs (converted from 500 gram Knoop).

FIGURE 170

MICROSTRUCTURE AND HARDNESS EXAMINATION OF HOT MACHINED TEST SAMPLES

Material 4340, 540 BHN, Induction Heated
Heat Treatment - Oil Quenched and Tempered

2% Nital Etch

Sample A *35 Rc. Sample B *57 Rc.

Photomicrograph (250X)

Sample A *35 Rc. Sample B *57 Rc.

Photomicrograph (1000X)

Upper surface of sample "A" is hot machined surface.
Upper surface of sample "B" is approximately 4-1/4 in. under upper surface of sample "A".

*Hardness taken 0.006 in. below upper surface shown in photomicrographs (converted from 500 gram Knoop).

FIGURE 171

EFFECT OF HOT MACHINING ON THE HARDNESS OF AISI 4340

HARDNESS vs DISTANCE FROM HOT MACHINED SURFACE (INDUCTION HEATED)

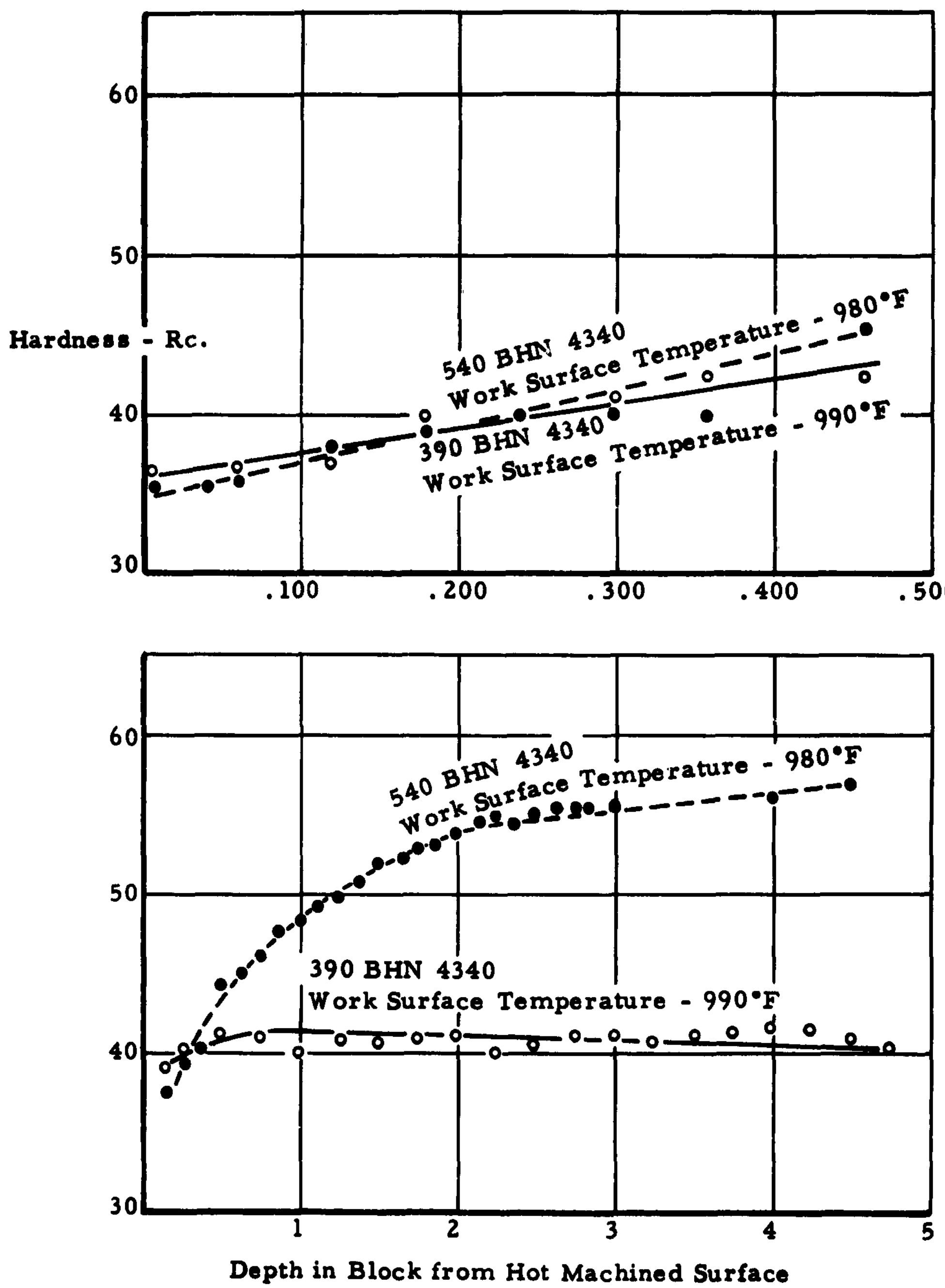
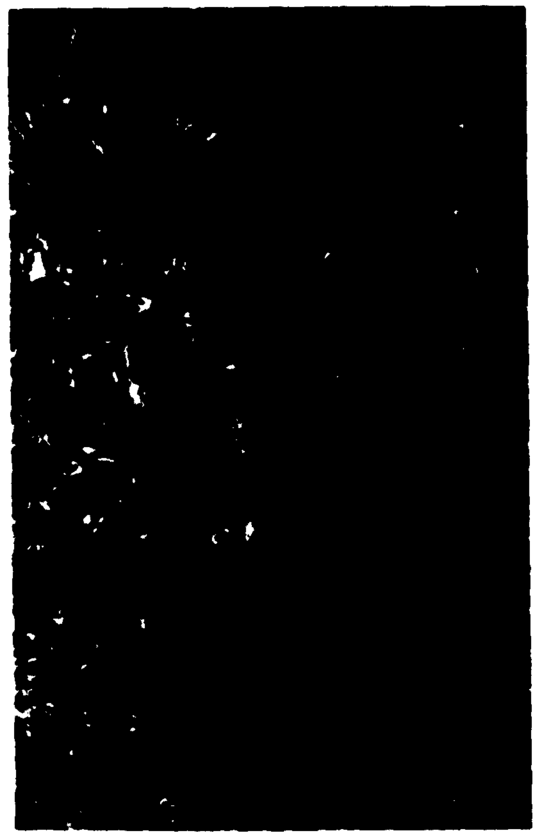


FIGURE 172

MICROSTRUCTURE AND HARDNESS EXAMINATION OF HOT MACHINED TEST SAMPLES

Material 4340, 390 BHN, RF Resistance Heating
Heat Treatment - Oil Quenched and Tempered

2% Nital Etch



Sample A	Sample B	Sample A	Sample B
*42-1/2 Rc.	*42-1/2 Rc.	*42-1/2 Rc.	*42-1/2 Rc.

Photomicrograph (250X)   Photomicrograph (1000X)

Upper surface of Sample A is hot machined surface.
Upper surface of Sample B is approximately 4-1/4 in. under upper surface of Sample A.

*Hardness taken 0.006 in. below upper surface shown in photomicrographs (converted from 500 gram Knoop).

FIGURE 173

MICROSTRUCTURE AND HARDNESS EXAMINATION OF HOT MACHINED TEST SAMPLES

Material 4340, 540 BHN, RF Resistance Heated
Heat Treatment - Oil Quenched and Tempered

2% Nital Etch

Sample A *43 Rc. Sample B *57 Rc.

Photomicrograph (250X)

Sample A *43 Rc. Sample B *57 Rc.

Photomicrograph (1000X)

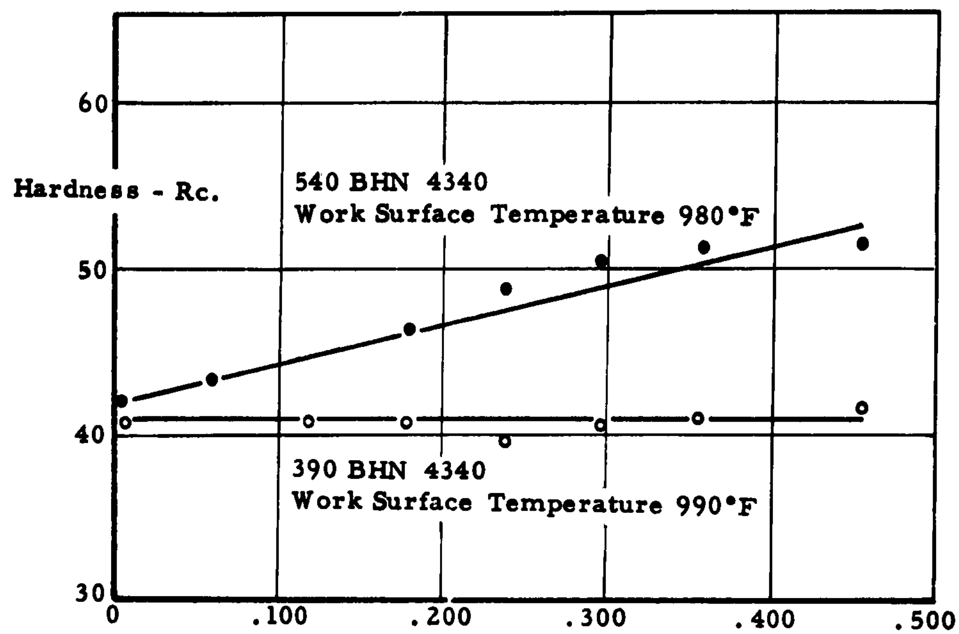
Upper surface of Sample A is hot machined surface.
Upper surface of Sample B is approximately 4-1/4 in. under upper surface of Sample A.

*Hardness taken 0.006 in. below upper surface shown in photomicrographs (converted from 500 gram Knoop).

FIGURE 174

EFFECT OF HOT MACHINING ON THE HARDNESS OF AISI 4340

HARDNESS vs DISTANCE FROM HOT MACHINED SURFACE (RF RESISTANCE HEATED)



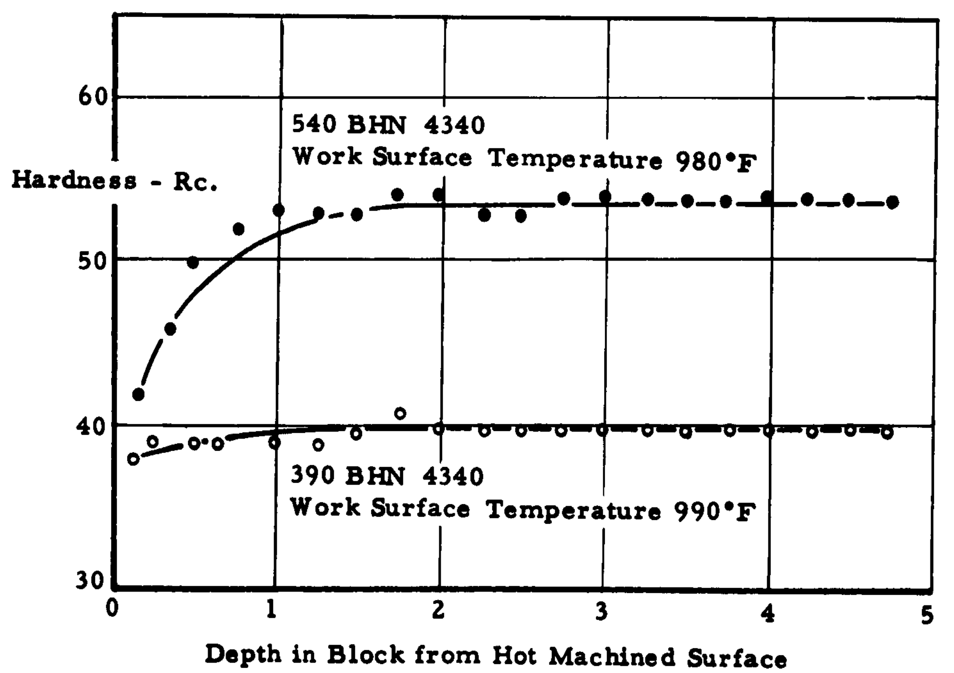


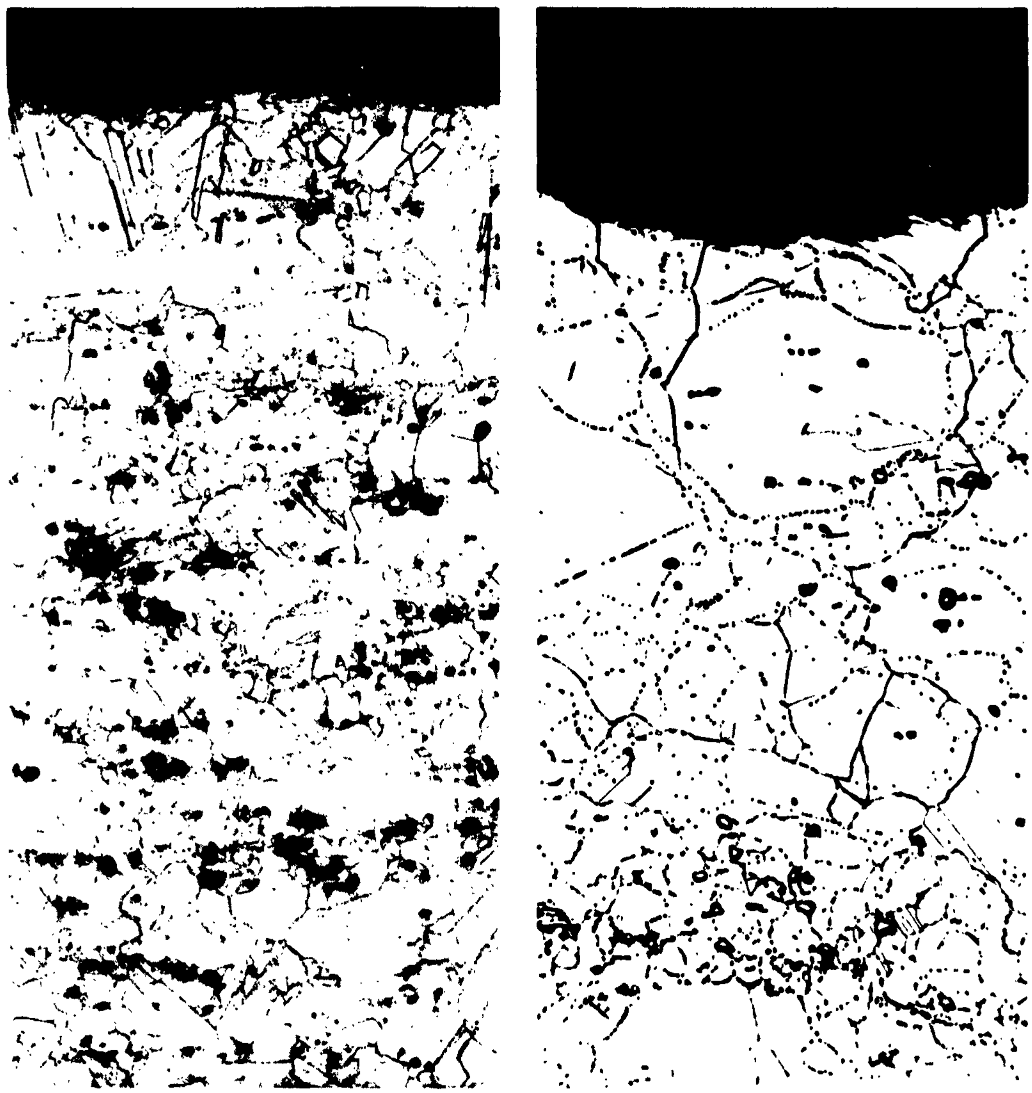
FIGURE 175

Microstructure Examination of Hot Machined Test Samples

Material - Rene 41

Heat Treatment - Solution Treated and Aged

Electrolytic Etch - 90% HC_L - 10% H_2O_2



100x 250x

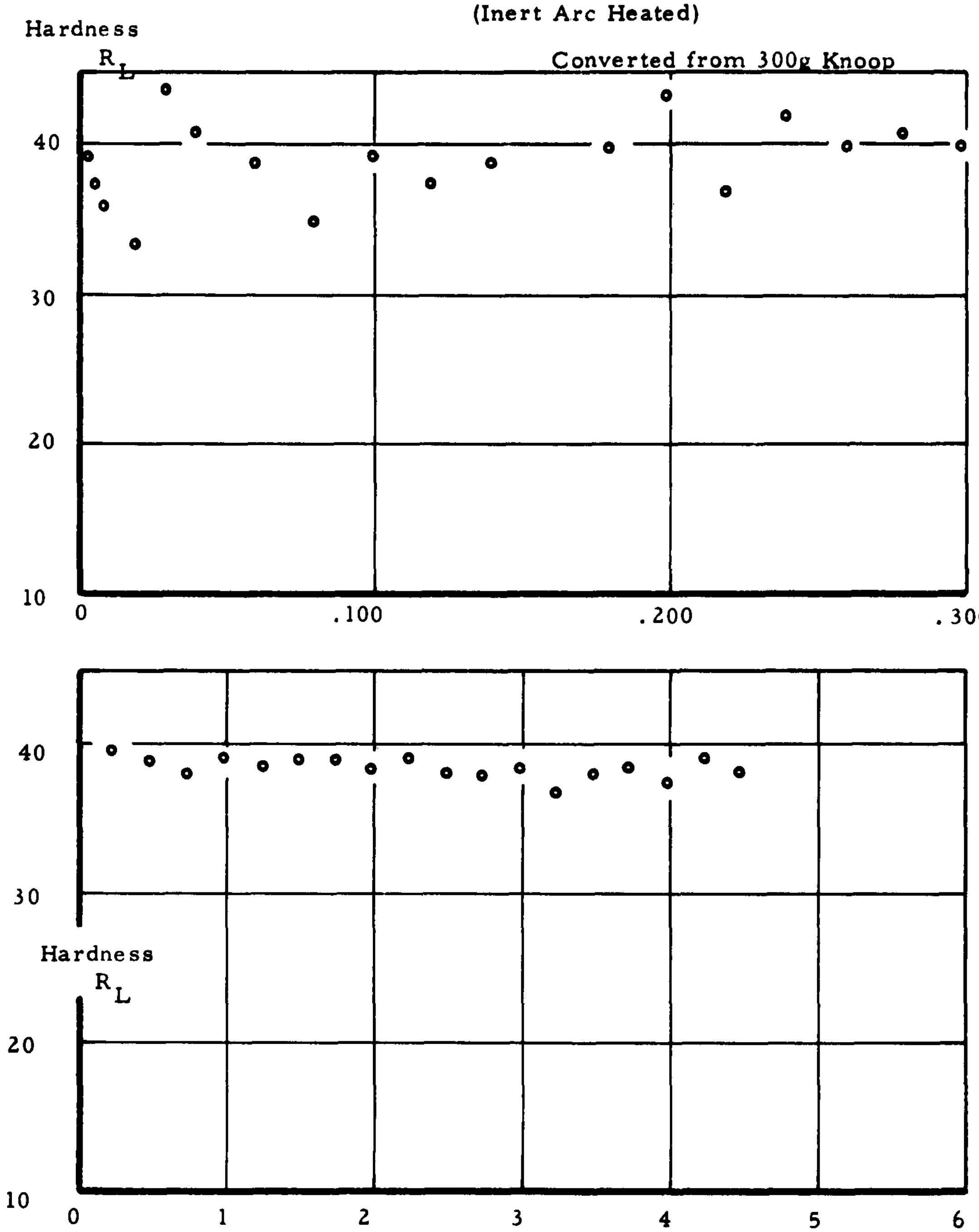
Hot Machined Surface at Top of Photomicrograph

FIGURE 176

Effect of Hot Machining on Hardness of Rene' 41

Hardness vs. Distance from Hot Machined Surface

(Inert Arc Heated)



Depth in Block from Hot Machined Surface (Inches)

FIGURE 177

Microstructure Examination of Hot Machined Test Samples

Material - Inconel X

Heat Treatment - Solution Treated and Aged

Electrolytic Etch - 90% HC_L - 10% H_2O_2

100 x   250 x

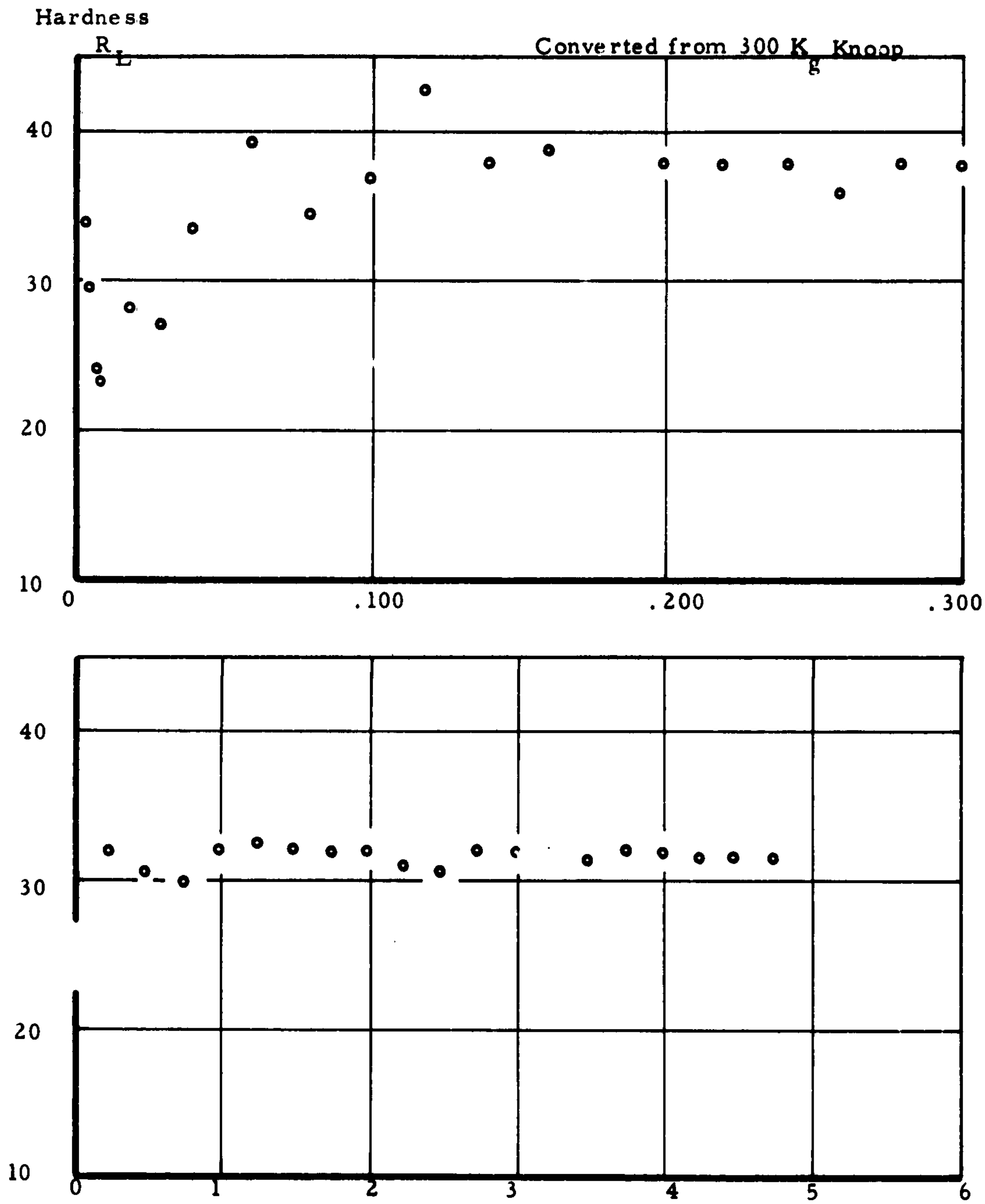
Hot Machined Surface at Top of Photomicrograph

FIGURE 178

Effect of Hot Machining on the Hardness of Inconel X

Hardness vs. Distance from Hot Machined Surface

(Inert Arc Heated)



Depth in Block from Hot Machined Surface (Inches)

FIGURE 179

Microstructure Examination of Hot Machined Test Samples

Material - Haynes Alloy No. 25

Heat Treatment - Solution Treated

Electrolytic Etch - 90% HC_L - 10% H_2O_2

100 x 250 x

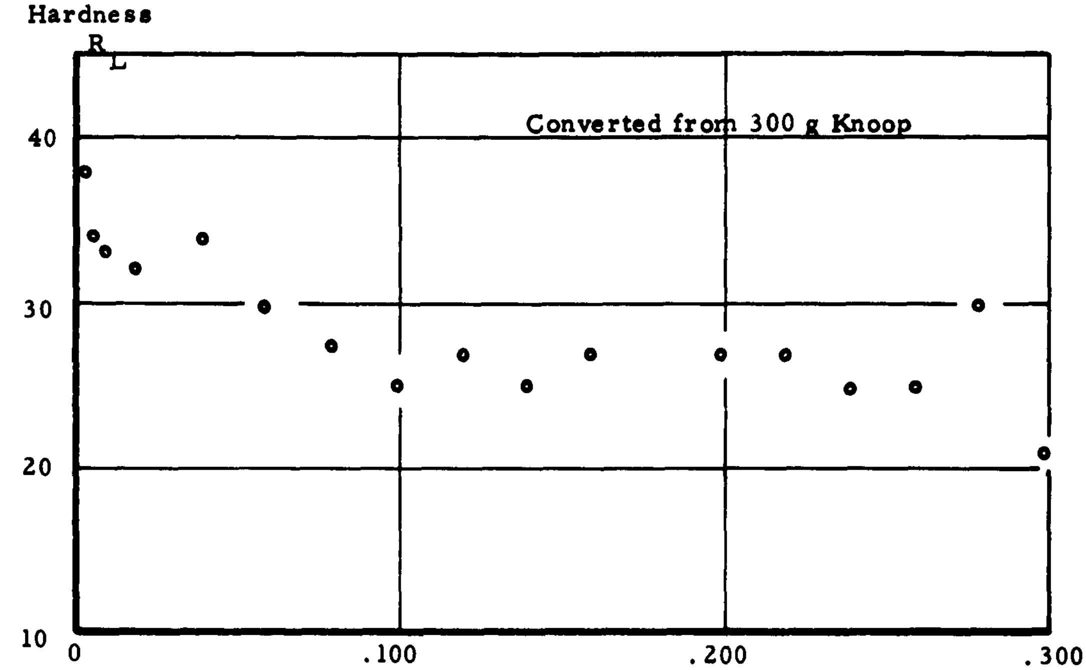
Hot Machined Surface at Top of Photomicrograph

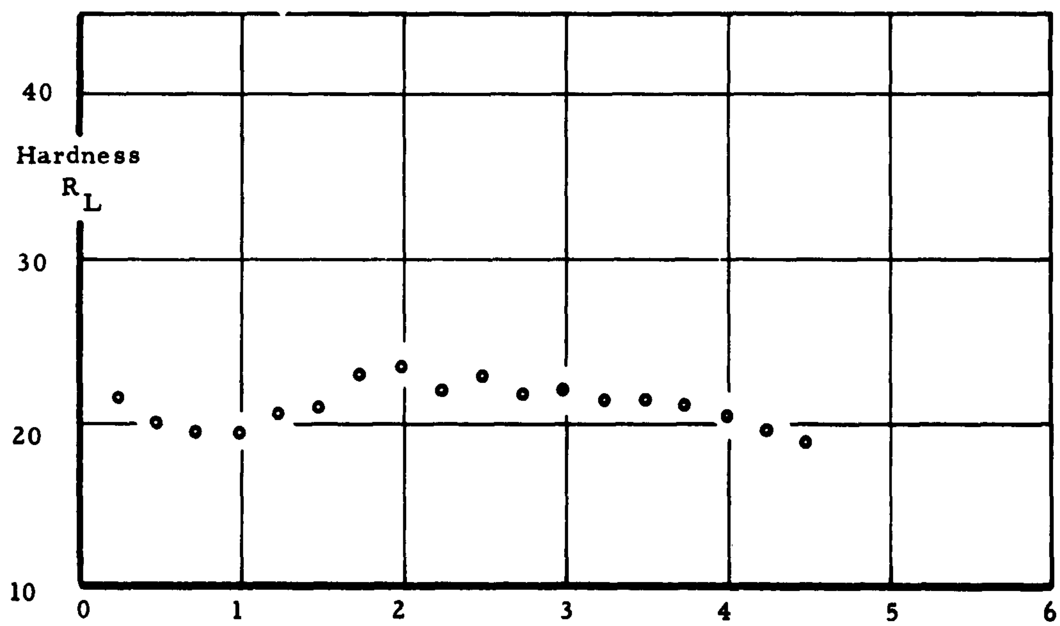
FIGURE 180

Effect of Hot Machining on the Hardness of Haynes 25

Hardness vs. Distance from Hot Machined Surface

(Inert Arc Heated)

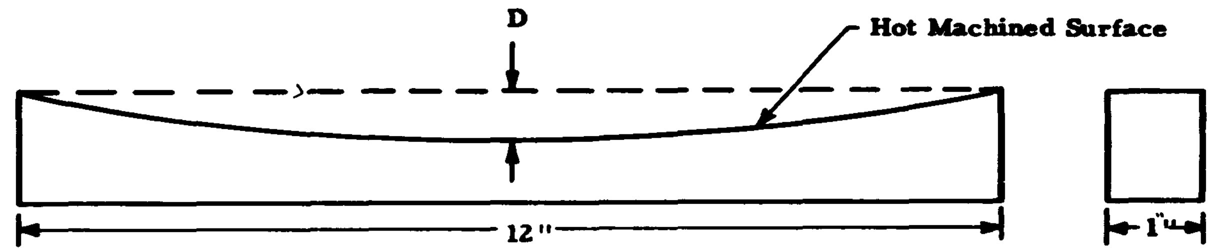




Depth in Block from Hot Machined Surface (Inches)

FIGURE 181

DISTORTION ENCOUNTERED IN HOT MACHINING (INDUCTION HEATED) WHEN MILLING



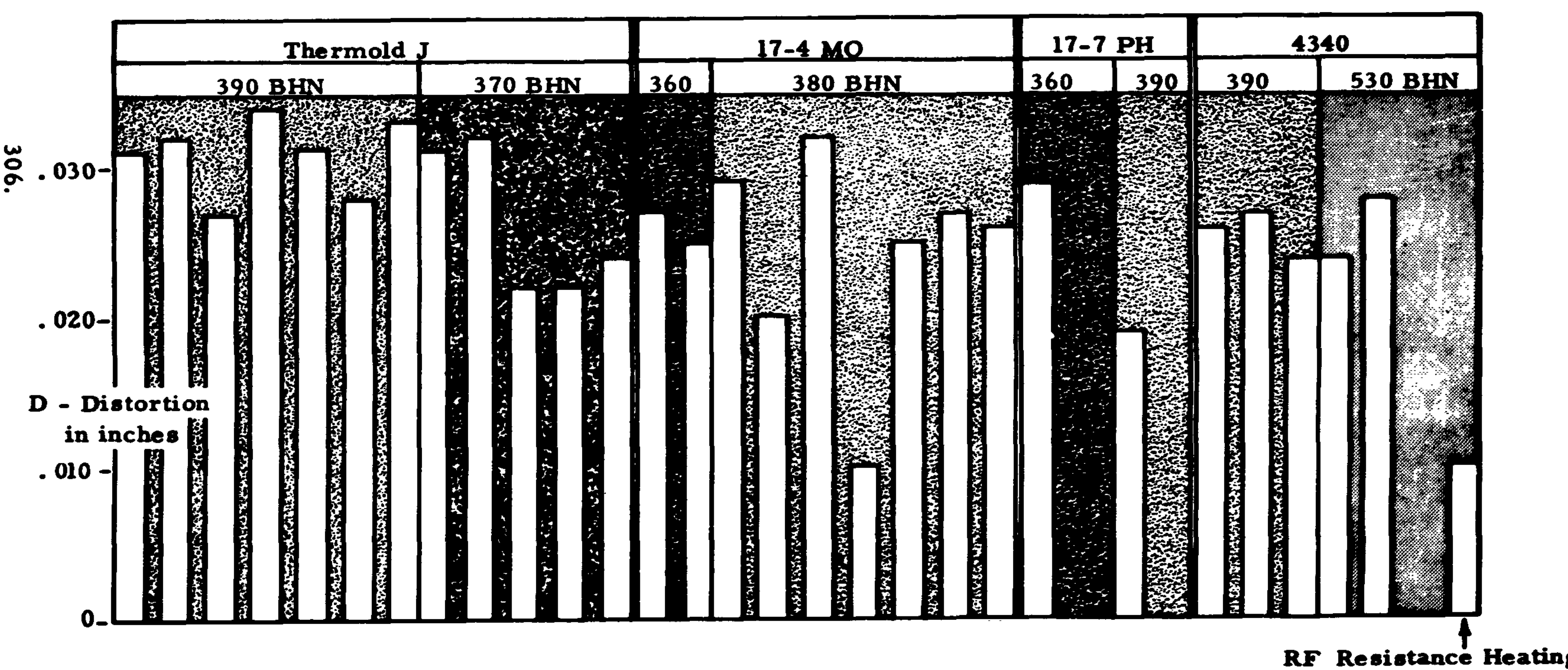


FIGURE 182

Distortion Encountered in Hot Machining (Inert Arc Heated) When Milling

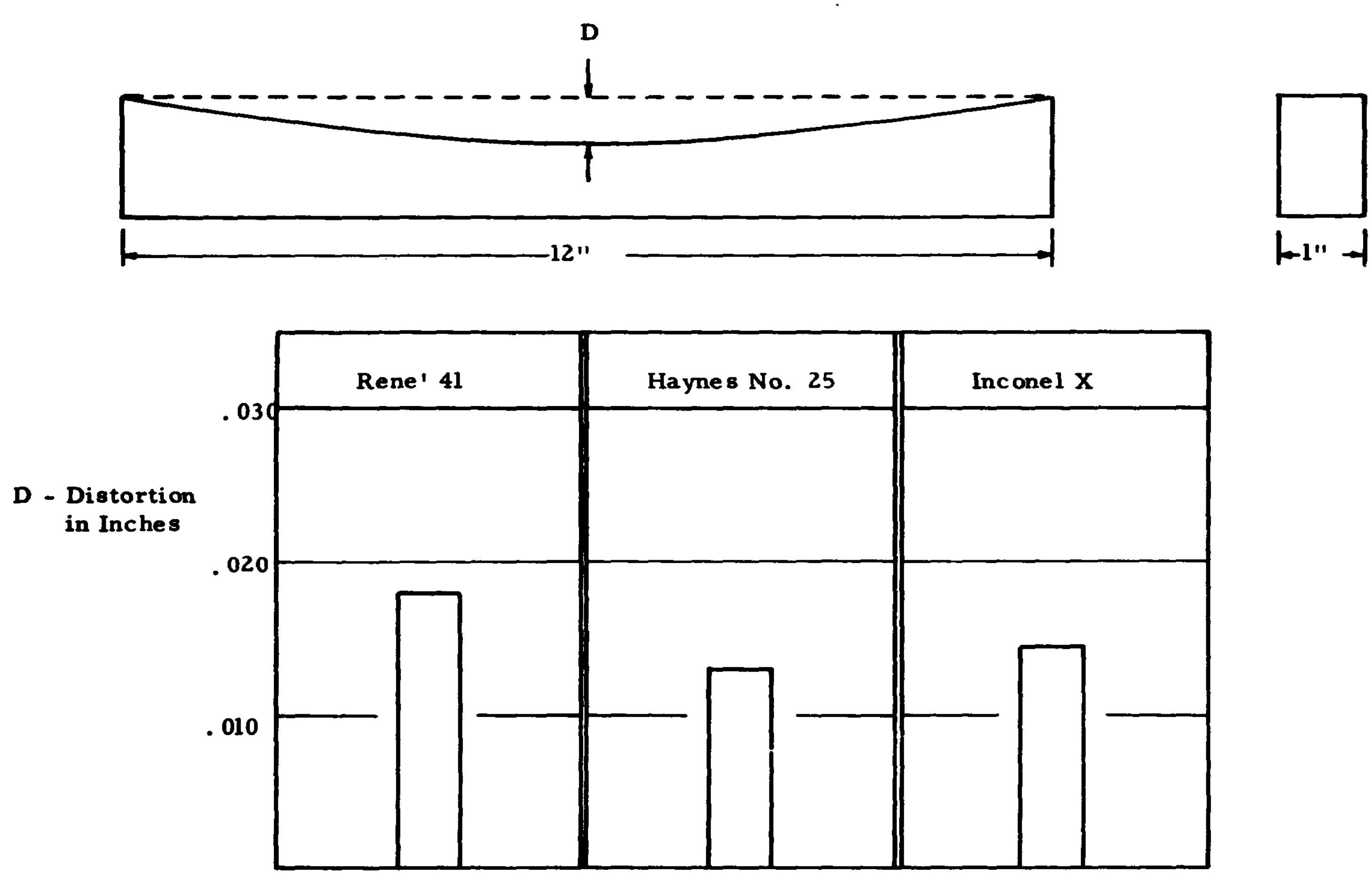


FIGURE 183

OPTIMUM TEMPERATURES FOR MAXIMUM TOOL LIFE

TURNING

Single Point Tool

Material	Temp.	BHN	Depth of cut inches	Carbide Tool: Feed ipr	Carbide Tool: Tool Matl.	Carbide Tool: Speed fpm	Tool Geometry: Side rake deg	Tool Geometry: Back rake deg	Tool Geometry: ECEA deg	Tool Geometry: SCEA deg	Tool Geometry: N. R inch
90 Ta 10 W	room	228	.030	.005	K-6 (C-2)	200	20	0	15	15	0
B 33 Cb	room	183	.030	.005	"	200	20	0	15	15	0
TZM Moly	room	241	.060	.008	"	300	20	0	15	15	0
W	500°F	321	.050	.009	K-11 (C-4)	20	-5	-5	15	15	1/32
C 120 AV Ti	room	311	.050	.009	K-6 (C-2)	200	6	0	15	15	1/32
B 120 VCA Ti	room	302	.050	.005	"	50	6	0	15	15	1/32

FACE MILLING

Material	Temp.	BHN	Carbide Tool: Depth of cut	Carbide Tool: Speed fpm	Carbide Tool: Feed in/tooth	Carbide Tool: Tool mat'l	Tool Geometry: IAR deg	Tool Geometry: RR deg	Tool Geometry: PCEA deg	Tool Geometry: FCEA deg	Tool Geometry: N. R. deg.	Eng. Angle deg
90 Ta 10 W	375°F	187	.050	204	.010	K-6 (C-2)	0	20	15	15	0	-45
B 33 Cb	room	179	.050	113	.010	"	0	20	15	15	0	-45
TZM Moly.	room	255	.050	669	.005	"	0	6	15	15	0	-45
W	800°F	286 to 302	.060	113	.010	"	0	6	15	15	1/32	-45
C 120 AV Ti	room	320	.050	464	.0177	"	0	6	15	15	1/32	-45
B120 VCA Ti	room	277	.050	204	.015	"	0	6	15	15	1/32	-45

ECONOMIC EVALUATION

SELECTION OF PARTS

The choice of typical parts to be used to compare the economics of machining at room and elevated temperature was based on six considerations.

(1) The part configuration must lend itself to heating and must be made of a material which has demonstrated that improvements can be obtained by machining at elevated temperatures.

(2) The part should be an actual part or have a typical configuration so that the true production problems will be encountered.

(3) The selected part or similar parts should be required in sufficient volume to justify the equipment cost for actual production.

(4) Since hot machining reduces the cutting time, sufficient stock removal should be required so that the savings would motivate a decision for change.

(5) The part must be simple so that no extreme conventional manufacturing difficulties are added to the problems of applying hot machining.

(6) The selected parts must provide a variety of operations and workpiece materials to fully evaluate the process.

With these considerations in mind, a survey of several manufacturers was conducted. After a presentation on the advantages and limitations of hot machining, personnel from Manufacturing Development Departments were asked for their recommendations on parts to which they thought hot machining could be applied. There was unanimous agreement that the parts should include a heat treated shaft or bolt, a fitting and a section of extrusion. It was furthermore agreed that in addition to high strength and stainless steel some work should be done on a heat resistant nickel base alloy.

Based on the above criteria and industries' recommendations, three parts were selected for evaluation. They were: 1) a main landing gear truck pivot from a commercial jet airliner made from 4340 steel heat treated to 220,000 - 240,000 psi (435 - 470 BHN); 2) a structural "T" section extrusion for the B-70 program made from Ph 15-7 Mo; and 3) a typical fitting, designed to fit the material available, was made from Rene' 41.

Each part, the manufacturing methods and cost analysis are described in detail in the following sections.

TRUCK PIVOT - MAIN LANDING GEAR

The truck pivot is used on a commercial jet airliner for pivoting the main landing gear when lowering or retracting. Four of the pivots are used in each airplane.

Description of Part

The truck pivot shown in Figure 184 is manufactured from 4340 bar stock, and heat treated to 220,000 to 240,000 psi (46 - 49 Rc or 435-470 BHN). Not all of the features were produced on the part for these tests, since some of the operations are performed at room temperature after heat treatment regardless of whether hot or conventional machining is used. The truck pivot (working drawings are shown in Figure 185) has two bearing surfaces requiring surface finishes of 63 microinches, a tolerance of .001 and concentricity of .002 T.I.R. The bearing surfaces are connected by a reduced tapered section. On one end there is a relieved flange and on the other 3-1/4-16 threads. A 1-1/2 inch diameter axial hole traverses the length of the entire piece.

Machining Operations

The sequence of machining operations required to conventionally machine the truck pivot was planned by Cincinnati's Manufacturing Planning Department. This plan was modified where necessary to properly utilize the characteristics of hot machining.

The sequence of operations for conventional machining was:

(1) Cut off the 4-1/2" diameter 4340 "as received" bar stock to 15-3/4" length.

(2) Face the ends to size - 15.50" and break corners on and engine lathe.

(3) Bore 1.50" diameter hole through piece (because of availability this operation was done on a Carlstadt deep hole driller instead of the conventional drill and ream operations).

(4) Rough turn to 4" diameter, chamfer one end to size, and chamfer the ends of the hole on an engine lathe.

(5) Turn diameters and taper to dimension + .020" on a tracer lathe.

(6) Quench and temper to 46 - 49 Rc as described under Work Materials.

(7) Grind bearing and thread diameters to size on a center type cylindrical grinder.

(8) Finish turn tapers to size on tracer lathe.

(9) Plunge turn reliefs for threads and flange, and chamfer the thread end.

(10) Shot peen.

For hot machining of this part, operations 1 through 4 were the same as those described for conventional machining. The subsequent operations are described below:

(5h) Quench and temper to 46 - 49 Rc as described under Work Materials.

(6h) Turn all diameters and taper to final size at a workpiece temperature of 700°F. No heat was added during the final cut when turning to dimension. This reduced distortion and made expansion calculations easier. Residual heat in the bar from previous cuts was sufficient to improve the machinability significantly.

(7h) Plunge turn reliefs for threads and flange, and chamfer the thread end with the workpiece at room temperature.

(8h) Shot peen.

<u>Machining Set-Up</u>

The truck pivot was machined on a 15 x 42 Cincinnati Tray-Top tracing lathe with a 7-1/2 hp motor, as shown in Figure 186. The workpiece was driven by heavy duty expanding mandrel inserted in the bored hole which was in turn mounted in a three jaw lathe chuck. A large (2-1/2") center mounted in needle bearings was used at the tailstock to support the work by riding the chamfered hole.

The power for radio-frequency controlled path resistance heating was supplied by a 30 KW, 1.2 mc Cincinnati Inductron.

The workpiece temperature was measured with a "Thermodot" radiation thermometer during the set-up cuts, to determine the proper Inductron heating machine settings. It was focused on the area just ahead of the cutting tool. No temperature measuring equipment was used during the actual production machining, since the heat output of the Inductron could be set at the required value to maintain the workpiece temperature.

Standard triangular throwaway insert lathe tool holders were used will grade 370 carbide and grade 0-30 oxide tools.

An estimate of the cost of this set-up is given under Comparison of Costs.

Comparison of Costs

In this section, as well as the comparison of costs sections describing the other parts, engineering and shop costs are given in terms of hours. We have assumed a labor plus burden rate of $10.00 per hour for conventional machining and a higher figure depending on the required capital expenditure for hot machining. A space is allowed for the reader to compute the dollar cost using his own particular labor and burden rate, since it is felt that this is the only way for each indivudal to truly evaluate the process.

Cost of the Set-Up: The cost of designing the set-up to machine the truck pivot was estimated by Cincinnati's Tool Design Department based on the designer being furnished some advanced background information on tentative designs rather than "starting from scratch" to develop a method. These costs are shown in Figure 187.

Capital Expenditures: While the cost of the r.f. resistance heating apparatus could be almost considered as capital expenditure, it is listed separately. It must be remembered, however, that even this design which was not intended to be extremely flexible can be used on any part having diameters between 2-1/4" and 4-1/4". It would be entirely possible to design equipment that could be used for any diameter between 1" and 6" to 8" on this 15" lathe (even greater ranges could be obtained on a larger machine) by only replacing the inexpensive ($3.50, labor and material) return conductor.

The only major capital expenditure is approximately $17,500 for the high frequency heating power supply. If this unit is used on a two shift basis (4000 hr/yr), it may be amortized in five years by adding $0.875 per hour to the burden rate. Therefore, in the subsequent section a rate of $10.875 per hour will be used for the hot machining calculations in place of $10/hr used for conventional machining.

It is suggested that the reader use his own amortization methods to determine the addition to the burden rate.

Time Study: The operations required to turn the main truck pivot were time studied by personnel from Cincinnati Time Study Department. Selected times were taken during the machining of several parts and corrected to standard data according to good time study practice to insure accurate results. The time study and the resultant costs are given in Figures 188 and 189.

It may be seen that using hot machining reduced the set-up costs from $55.35 to $48.00 (a 13% savings) and the machining cost from $24.85 to $19.55 (a 21% savings) when compared to the conventional method. It may be argued that even without the use of hot machining the costs could be reduced by substituting a finish turning operation with oxide tools for the grinding operation, but even so, hot machining eliminates the necessity of two lathe set-ups, one before and one after heat treatment, thereby reducing costs.

If a larger lathe were available with approximately 15 hp the depth of cut could be increased to 1/4 inch and the cutting time reduced to 11 minutes cold and 16.2 minutes hot. This would similarly reduce the total times and costs to:

Conventional Machining	Total Set-up	$55.35
	Total Standard	23.05
Hot Machining	Total Set-up	$46.23
	Conventional Standard	10.00
	Hot Standard	6.70
	Total Standard	$16.70

This is a 28% reduction in cost for machining each truck pivot.

"T" SECTION EXTRUSION

The "T" section extrusion of Ph 15-7 Mo to be machined all over is one of a family of stiffners used on the B-70. Several miles of stiffners are required for each aircraft. The extrusions are machined in the solution treated (annealed) condition, brazed to the skin and the whole assembly heat treated to precipitation harden the structure.

Description of the Part

A photograph of the "T" extrusion before and after machining is shown in Figure 190, and an engineering drawing is given in Figure 191. The full size sketch in Figure 191 should be noted to understand the difficulties entailed in machining this part. The extrusion to be machined was Ph 15-7 Mo precipitation hardening stainless steel in the solution treated condition. These extrusions are normally milled in lengths of 17 feet or longer by a process of "continuous milling". This method consists of pulling the workpiece through stationary "slip" fixtures on either side of the cutter with a chain or other mechanism. Since the table feed mechanism is not used to feed the part excessive table travel is not required. However, for the purpose of these tests it was felt that shorter workpieces (27" long) would provide the practical evaluation without requiring the construction of the special fixturing required for continuous milling. Several features of continuous milling, such as the stationary (i.e. non-feeding) clamping devices, were retained to demonstrate the feasibility of hot machining on a continuous milling set-up. The entire set-up is described in a separate section.

Machining Operations

The operations necessary to machine the extrusion and their sequence were planned by research personnel with the assistance of the Manufacturing Planning Department, and were based on the sequence presently used to manufacture this part. The sequence of operation was the same for conventional and hot machining with cutting speeds and feeds chosen to yield equivalent tool lives at room or the elevated temperature.

The sequence of operations was as follows:

(1) Straddle mill the base and both sides of the base to size.

(2) Mill the top of the extrusion to the correct height (a photograph taken after this operation is shown in Figure 190, center)

(3) Straddle mill both sides to size with the proper radius.

Machining Set-Up

The extrusion was machined on No. 3 Cincinnati horizontal dial type milling machine. The same Cincinnati 1.2 mc, 30 kw, Inductron power supply used for machining the truck pivot was used to supply the r.f. resistance heating power used for these tests. It should be noted that both tests were conducted almost simultaneously and the power supply was alternately used with the two set-ups. Switching the power from one machine to the other involved loosening two screws to change the power leads and moving the start-stop buttons. This took about 10 minutes. With quick connect couplings and dual controls the unit could be switched between machines in the shop in 1 to 2 minutes for alternate use of the power supply.

The permanent set-up used for all operations, hot and cold, consisted of a 6" structural "I" beam clamped in back of the milling table as shown in Figure 192. Eight channels, four on each side of the cutter, were bolted to the "I" beam to provide supports for the clamping air cylinders. The air cylinders held the extrusion against the fixtures through a clevis and brass roller arrangement. Each air cylinder was individually controlled so that the 80 psig air pressure would be applied only when the clamp was over the workpiece. While for these tests the air valves were manually controlled, it would be easy to control them automatically in production with limit switches. The channel just in front of the cutter was also used as a support for one r.f. resistance heating electrode. This arrangement will be described later.

Two fixtures were used on the milling machine table. The first, shown in Figures 193, 194 (operation 1), 195 and 196 (operation 2), was used to machine the base and top of the extrusion. It consisted of a long vise where with proper spaces the workpiece could be clamped with set screws. The second fixture shown in Figures 197 and 198 (operation 3) was used for machining the sides of the extrusion. Since the base of the "T" would be only .060 thick after machining, there was insufficient stock for clamping and the fixture was used only to position the work. The air cylinders and the downward forces from climb milling were relied on to keep the extrusion in the fixture.

A channel clamped to the knee of the milling machine was used as a support to carry the other heating electrode.

The "Thermodot" radiation pyrometer was used to determine the required induction setting for proper workpiece temperature during preliminary tests but was not needed during the production tests, since proper operating conditions had already been established. Under shop conditions a radiation pyrometer would be used during set-up to determine the power supply settings required for production.

The cutters were arbor mounted side mills with grade 78B brazed inserts. The geometries of the cutters are shown in Figure 199.

Comparison of Costs

In this comparison of costs we have assumed a labor + burden rate of $10.00 per hour ($.167/minute) for engineering and shop time where hot machining is not used. Since the same capital expenditure is required as with the truck pivot, a rate of $10.875 per hour ($.181/minute) is also used for hot machining operations.

Cost of the Set-Up: The cost of the set-up for machining the extrusion was estimated by Cincinnati's Tool Design Department and, again, was based on the premise that the designer has the knowledge necessary to design the set-up. The costs are shown in Figure 200.

Time Study: The three operations necessary to machine the extrusion were studied by Cincinnati's Time Study Department. The times were corrected for operator skill and exertion to standard data and the resultant costs are given in Figures 201 and 202. It can be seen that the cost of machining the 27" length of extrusion is reduced from $6.31 to $4.83 by applying hot machining but that the set-up cost is increased by $5.16 to $23.53.

If we make the assumption that the various loading and machine handling times are the same for the 17 feet length of extrusion and that the lot size is 102 feet (6-17' lengths), we can determine the handling time and cutting time. The handling time is six times the handling time for one piece. The cutting time is the lot length (12 x 102 inches) divided by the length of one piece (27 inches) and multiplied by the cutting time for one piece. A comparison of the times and costs are shown in Figure 203. This comparison shows that the cost per foot can be reduced from $2.00 to $1.27, a 36% savings when the lot size is 102 feet. A larger lot size will reduce the cost still further.

FITTING

The fitting to be machined from Rene' 41 is not an actual design, but rather a part which may be required in the future. Parts of similar configurations made from martensitic stainless steels are being used for present aircraft. The size of the fitting was determined by the availability of workpiece material.

Description of Part

The fitting that was to be manufactured from Rene' 41 is shown in Figure 204. Difficulties encountered with the machinability of Rene' 41 did not allow the use of hot machining on this part, so, consequently, no economic comparison was made. In an attempt to overcome the difficulties, a study of the effect of workpiece parameters on conventional and hot machining tool life was performed. This investigation of the machinability of Rene' 41 is given in the section on Milling Tests.

TRUCK PIVOT - MAIN LANDING GEAR

FIGURE 184

FIGURE 185

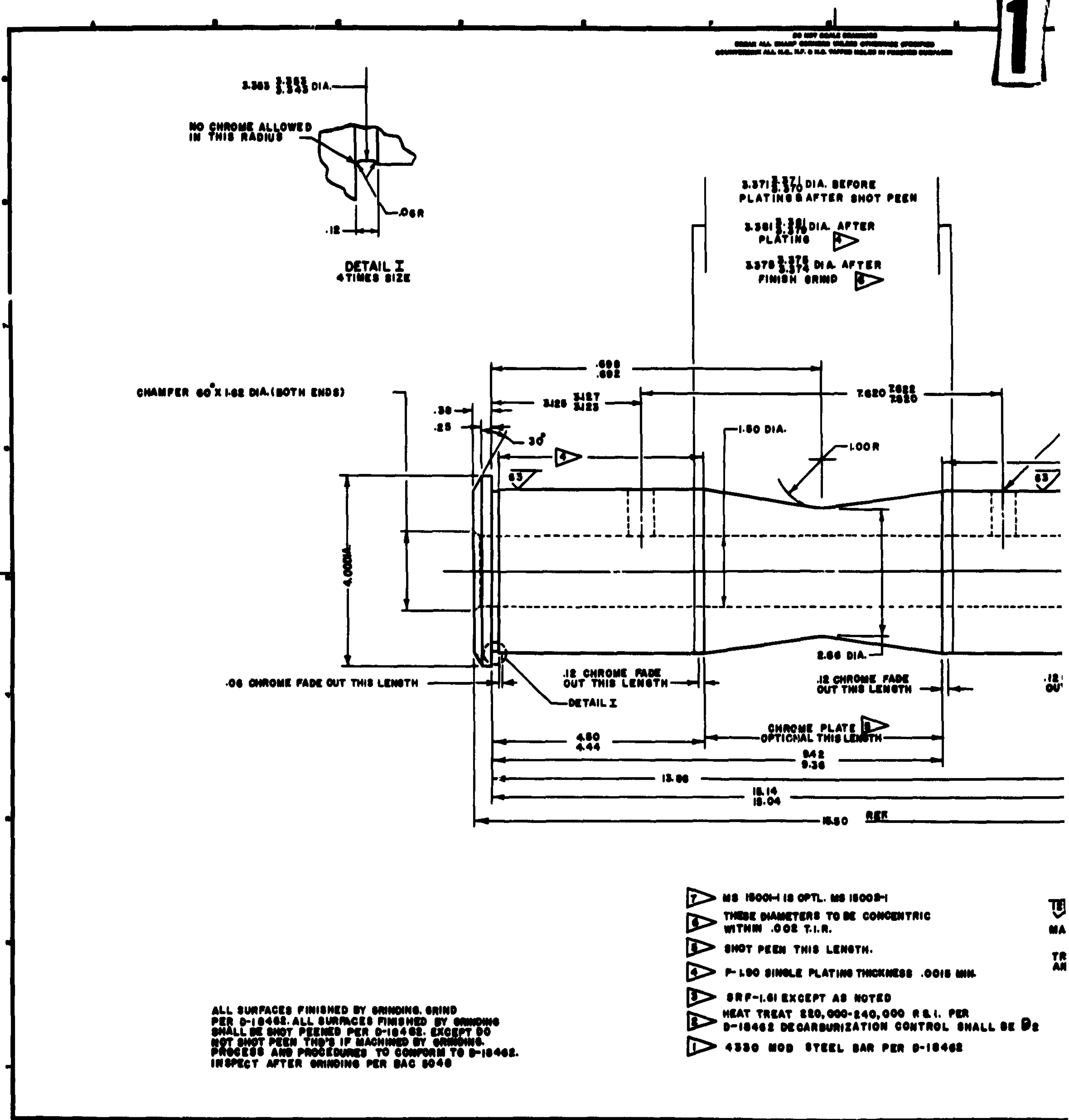
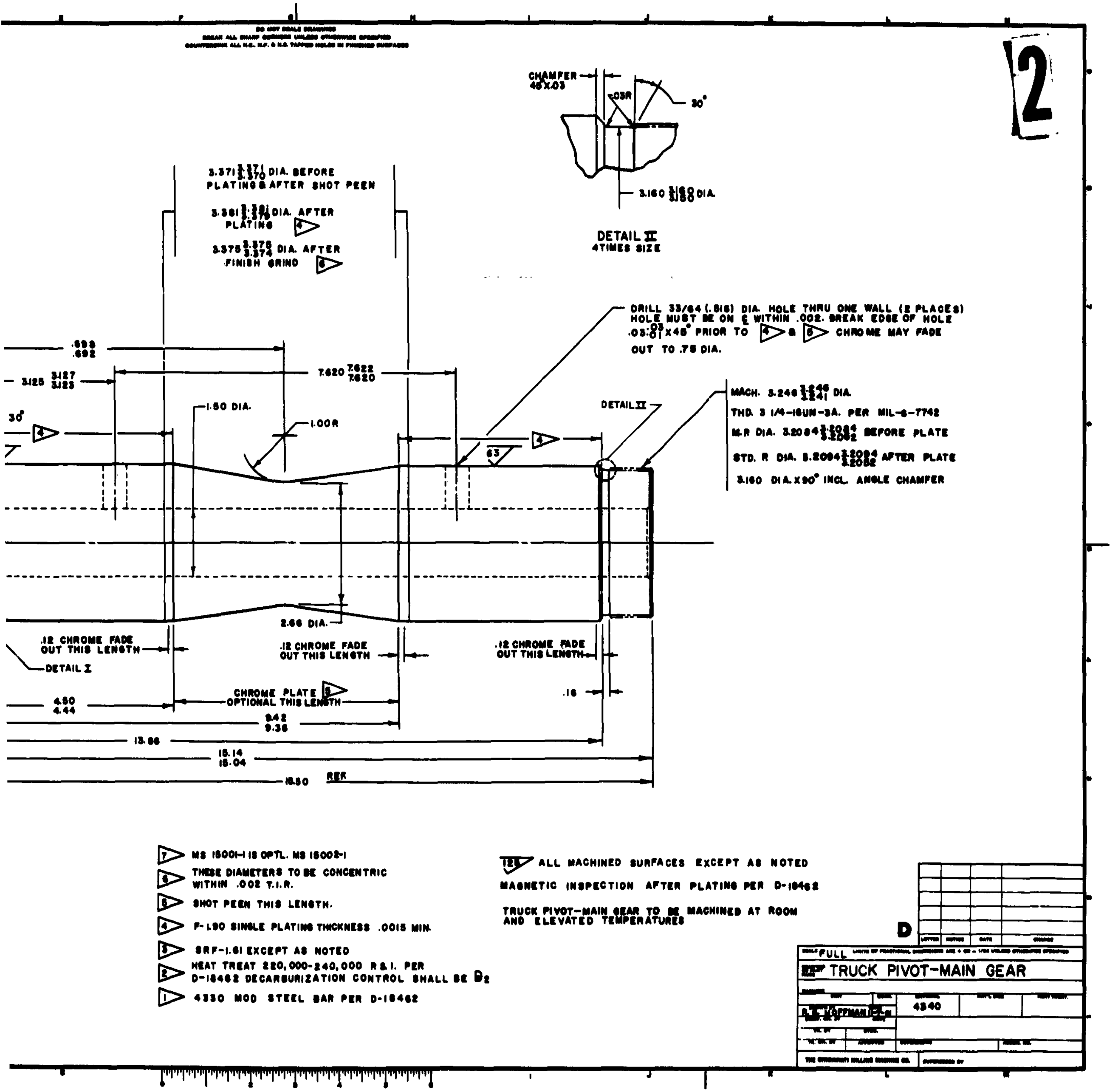

DETAIL I
4 TIMES SIZE
NO CHROME ALLOWED IN THIS RADIUS
.06 R
.12
3.371 DIA. BEFORE PLATING & AFTER SHOT PEEN
3.381 DIA. AFTER PLATING
3.375 DIA. AFTER FINISH GRIND
CHAMFER 60° X 1.62 DIA. (BOTH ENDS)
1.50 DIA.
1.00 R
2.66 DIA.
4.00 DIA.
.06 CHROME FADE OUT THIS LENGTH
.12 CHROME FADE OUT THIS LENGTH
DETAIL I
CHROME PLATE OPTIONAL THIS LENGTH
13.96
16.50 REF
MS 15001-1 IS OPTL. MS 15002-1
THESE DIAMETERS TO BE CONCENTRIC WITHIN .002 T.I.R.
SHOT PEEN THIS LENGTH.
P-1.90 SINGLE PLATING THICKNESS .0015 MIN.
SRF-1.61 EXCEPT AS NOTED
HEAT TREAT 220,000-240,000 P.S.I. PER D-18462 DECARBURIZATION CONTROL SHALL BE D2
4330 MOD STEEL BAR PER D-18462
ALL SURFACES FINISHED BY GRINDING. GRIND PER D-18462. ALL SURFACES FINISHED BY GRINDING SHALL BE SHOT PEENED PER D-18462. EXCEPT DO NOT SHOT PEEN THD'S IF MACHINED BY GRINDING. PROCESS AND PROCEDURES TO CONFORM TO D-18462. INSPECT AFTER GRINDING PER BAC 5046

FIGURE 185



2
CHAMFER 45°X.03
.03R
30°
3.160 DIA.
DETAIL II
4 TIMES SIZE
DIA. BEFORE PLATING & AFTER SHOT PEEN
DIA. AFTER PLATING
DIA. AFTER FINISH GRIND
DRILL 33/64 (.516) DIA. HOLE THRU ONE WALL (2 PLACES) HOLE MUST BE ON ℄ WITHIN .002. BREAK EDGE OF HOLE X45° PRIOR TO 4 & 6 CHROME MAY FADE OUT TO .75 DIA.
MACH. DIA.
THD. 3 1/4-16UN-3A. PER MIL-S-7742
BEFORE PLATE
AFTER PLATE
3.160 DIA. X 90° INCL. ANGLE CHAMFER
DETAIL II
1.50 DIA.
1.00R
63
2.66 DIA.
.12 CHROME FADE OUT THIS LENGTH
DETAIL I
CHROME PLATE OPTIONAL THIS LENGTH
.16
13.86
15.14
15.04
15.50 REF
MS 15001-1 IS OPTL. MS 15002-1
THESE DIAMETERS TO BE CONCENTRIC WITHIN .002 T.I.R.
SHOT PEEN THIS LENGTH.
F-1.90 SINGLE PLATING THICKNESS .0015 MIN.
SRF-1.61 EXCEPT AS NOTED
HEAT TREAT 220,000-240,000 P.S.I. PER D-18462 DECARBURIZATION CONTROL SHALL BE D2
4330 MOD STEEL BAR PER D-18462
ALL MACHINED SURFACES EXCEPT AS NOTED
MAGNETIC INSPECTION AFTER PLATING PER D-18462
TRUCK PIVOT-MAIN GEAR TO BE MACHINED AT ROOM AND ELEVATED TEMPERATURES
D
FULL
TRUCK PIVOT-MAIN GEAR
4340

MACHINING THE TRUCK PIVOT USING R. F. RESISTANCE HEATING

Workpiece, Electrodes and Tool on the Tracer Lathe

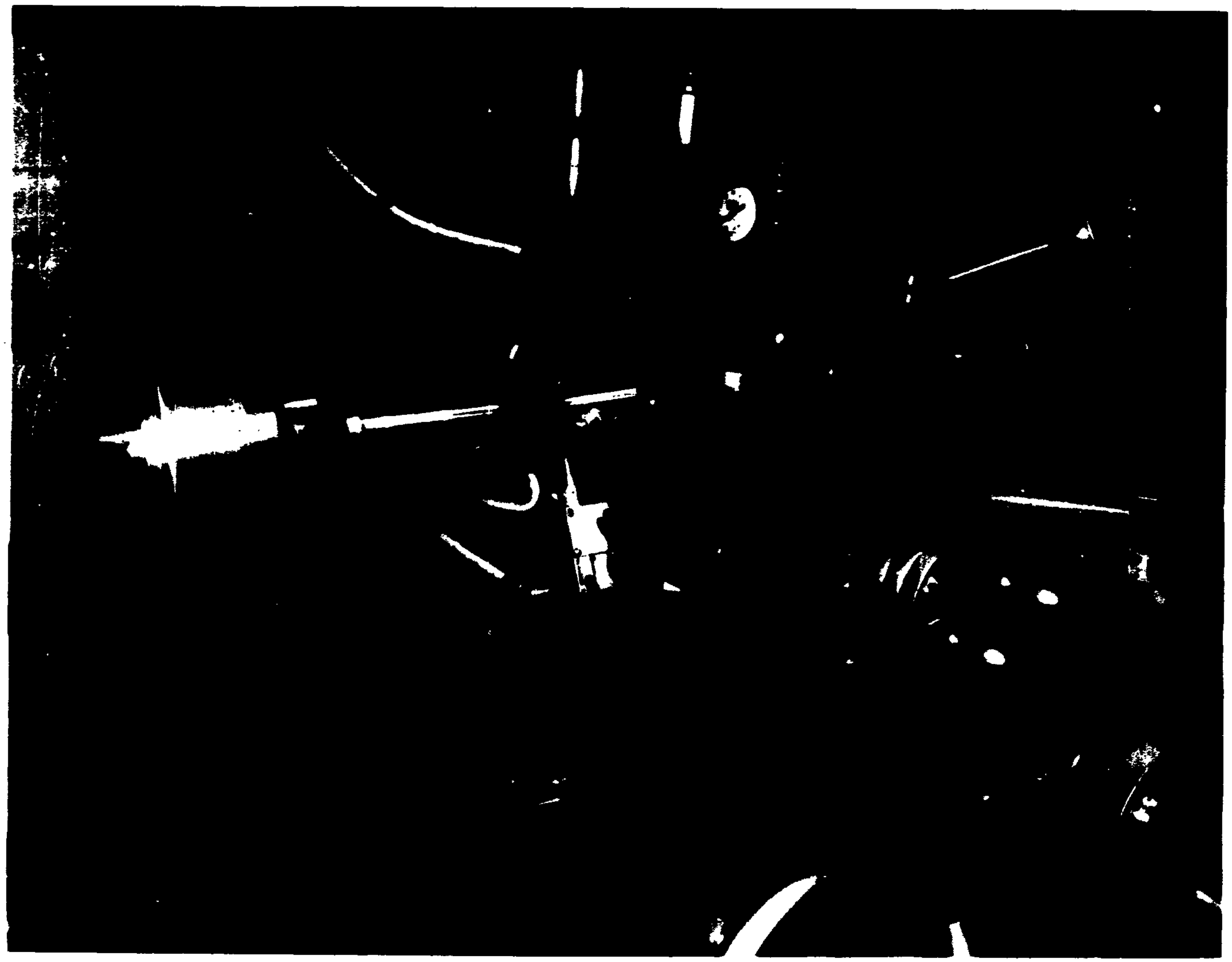


FIGURE 186

SET-UP COSTS

Main Truck Pivot

	Design Hours	Design Cost	Your Design Cost	Construction Hours	Const. Cost	Your Const. Cost	Materials
Conventional Machining							
Template	4	$ 40		10	$ 100		$ 2.00
Expanding Mandrel							300.00
Live Center							270.00
Lathe Tool							10.00
Total	4	$ 40		10	$ 100		$582.00
Total Cost $722							
Your Total Cost							
Hot Machining							
The above items	4	$ 40		10	$ 100		$582.00
Bracket-Cross Slide (including electrodes)	75	750		125	1,250		35.00
Air cylinders and equipment							60.00
Transmission Lines	1	10		6	60		55.00
Total	80	$800		141	$1,410		$732.00
Total Cost $2942							
Your Total Cost							

FIGURE 187

TIME STUDY AND COST DATA
Main Truck Pivot

Elements	Units Elevated Temperature	Units Room Temperature
Load and unload (mandrel and crane)	7.82	7.82
Set dial for depth	5.63	5.03
Position to cut	6.50	5.80
Set to heat	1.00	-
Cutting	27.20*	22.00
Total Units	48.15	39.65
Total set up allowed	70	50

* One extra traverse cut is required for hot machining to bring part to final size.

Operations	Total Time Elevated Temperature 700°F Standard	Total Time Elevated Temperature 700°F Set-Up	Room Temperature Standard	Room Temperature Set-Up
All machining prior to turning (items 1-4)*	43	146	43	146
Turn (cold to grdg. size hot to final size)	48	70	40	50
Grind OD to size*	-	-	37	37
Finish turn taper to size	-	-	12	50
Turn reliefs*	8	40	8	40
Shot peen*	9	9	9	9
Total Units Allowed	108		149	
Total Set-Up Allowed		265		332

* The times for these items were taken from standard data and were not time studied at this time.

FIGURE 188

COST

	Minutes	Cost	Your Cost
Conventional Machining at $10/hr or $.167/min			
Total Set-Up	332	$55.35	
Total Standard	149	$24.85	
Hot Machining at $10.875/hr or $.181/min for hot machining operation set-up	70	$12.67	
at .167/min for conventional operation set-up	195	$33.56	
Total Set-Up		$46.23	
Total Hot Machining Standard	48	8.69	
Total Conventional Standard	60	10.00	
Total Standard		$18.69	

FIGURE 189

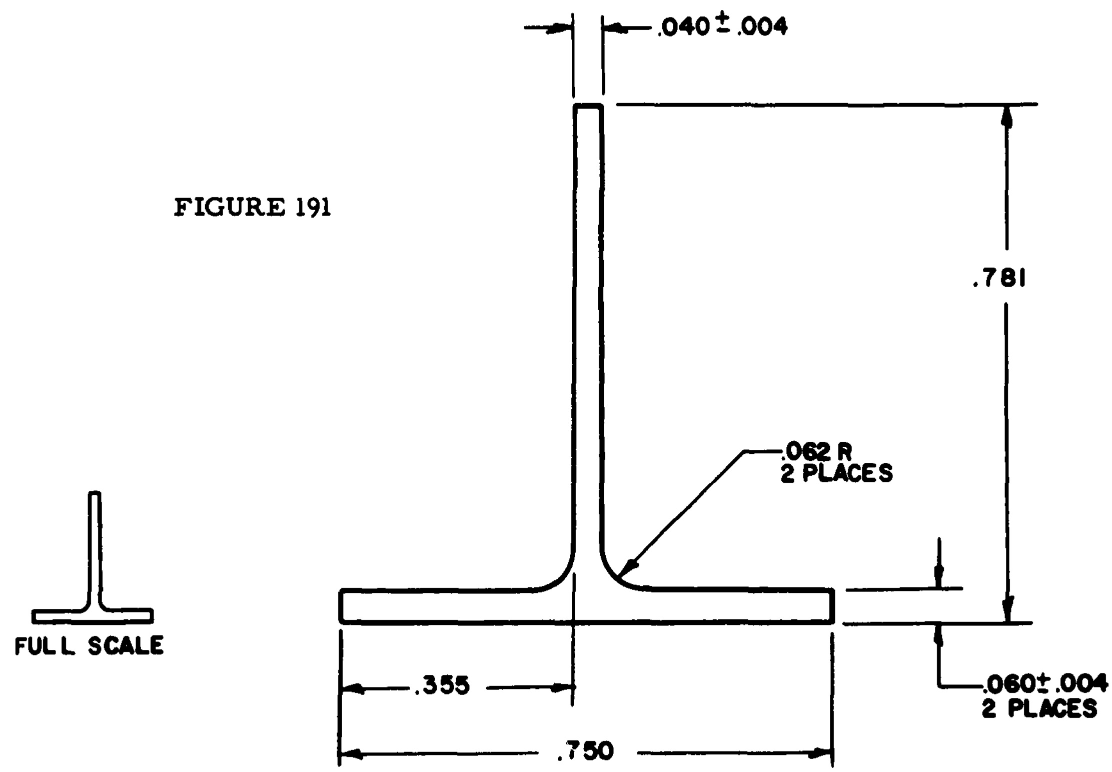
PH 15-7 MO "T" EXTRUSION

Before Machining, after Operations No. 1 and No. 2, after Machining

FIGURE 190

DO NOT SCALE DRAWINGS
BREAK ALL SHARP CORNERS UNLESS OTHERWISE SPECIFIED
COUNTERSINK ALL N.C., N.F. & N.S. TAPPED HOLES IN FINISHED SURFACES

FIGURE 191



STRUCTURAL SHAPE TO BE MACHINED
FROM AN EXTRUSION AT ROOM
AND ELEVATED TEMPERATURES

SCALE	LIMITS OF FRACTIONAL DIMENSIONS ARE + OR − 1/64 UNLESS OTHERWISE SPECIFIED				
DRAWING OR PART NAME	**SHAPE-STRUCTURAL**				
MACHINE					
UNIT	QUAN.	MATERIAL: 15-7 PRECIP. STAINLESS	MAT'L SIZE: HARDENING STEEL	HEAT TREAT.	
DRAWN BY: G. RUSS	DATE: 11-1-61				
DRAW. CH. BY	DATE				
TR. BY	STDS.				
TR. CH. BY	APPROVED	SUPERSIDES		ASSEM. NO.	
THE CINCINNATI MILLING MACHINE CO.		SUPERSEDED BY			

MACHINING THE "T" EXTRUSION

Fixture, Air Cylinder Hold-Downs, Heat Control Panels

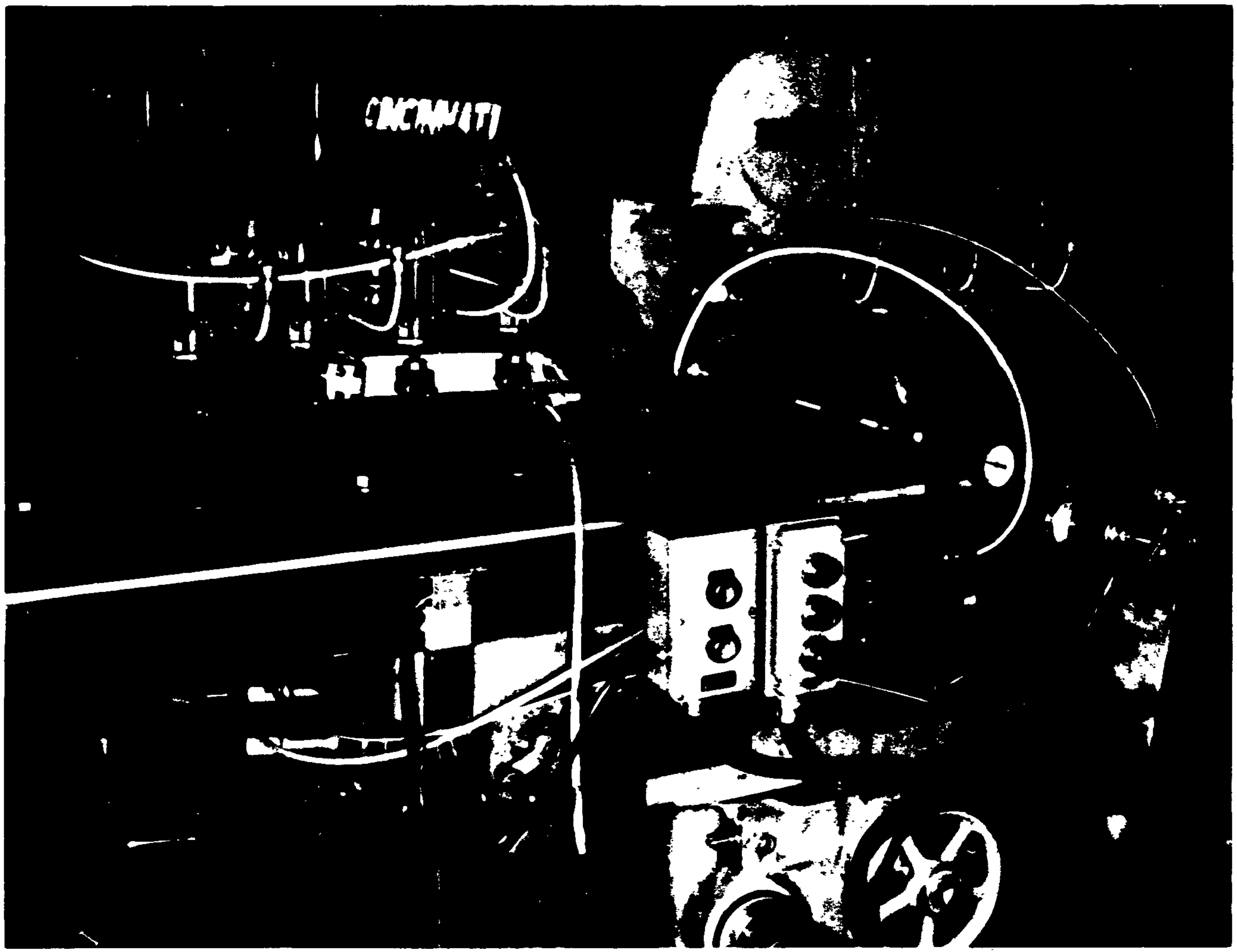


FIGURE 192

MACHINING THE "T" EXTRUSION OPERATION NO. 1

Hold-Down, Workpiece, Electrode and Return Conductor, Cutters

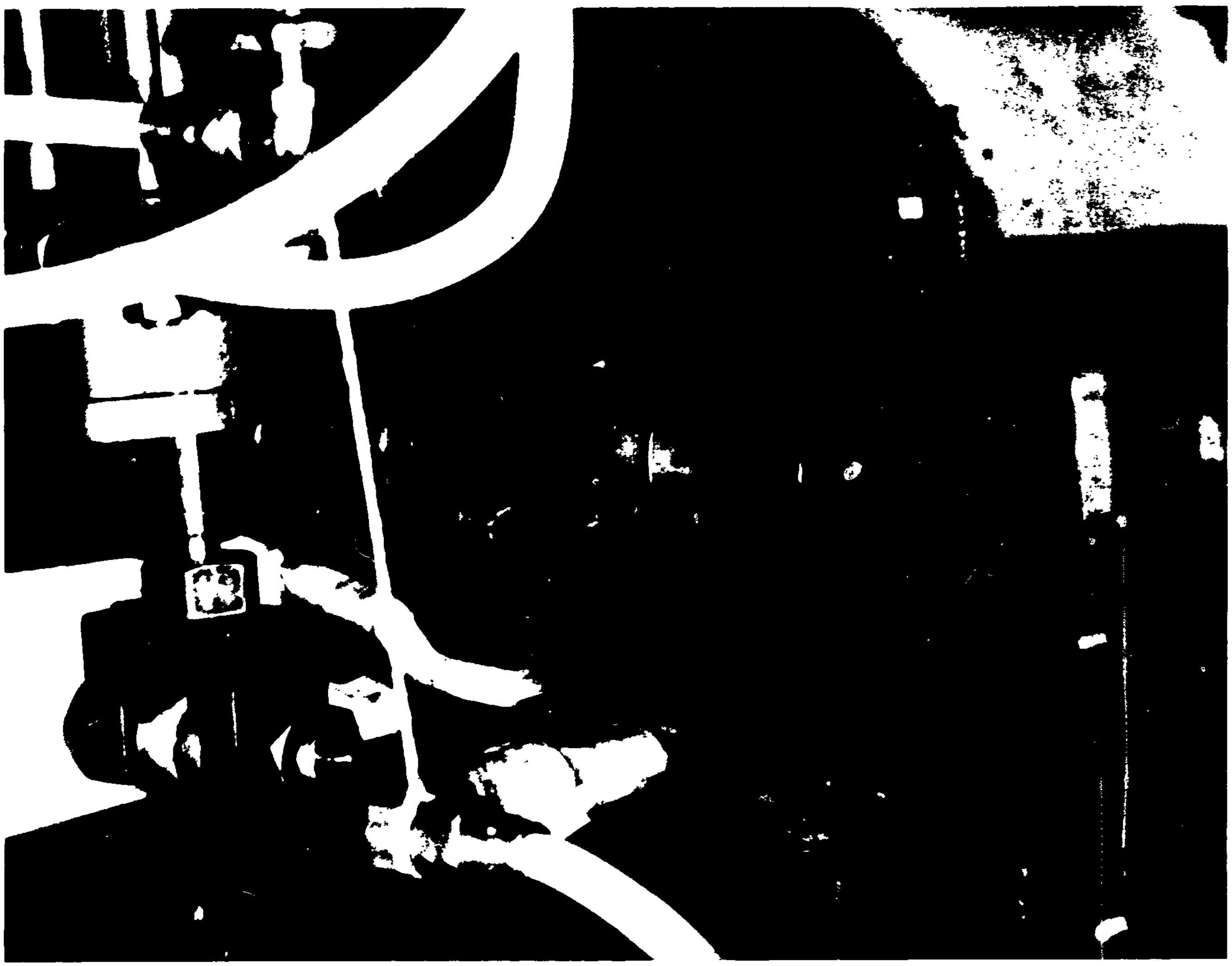


FIGURE 193

MACHINING THE "T" EXTRUSION OPERATION NO. 1

Electrodes, Workpiece, Fixture, Cutters

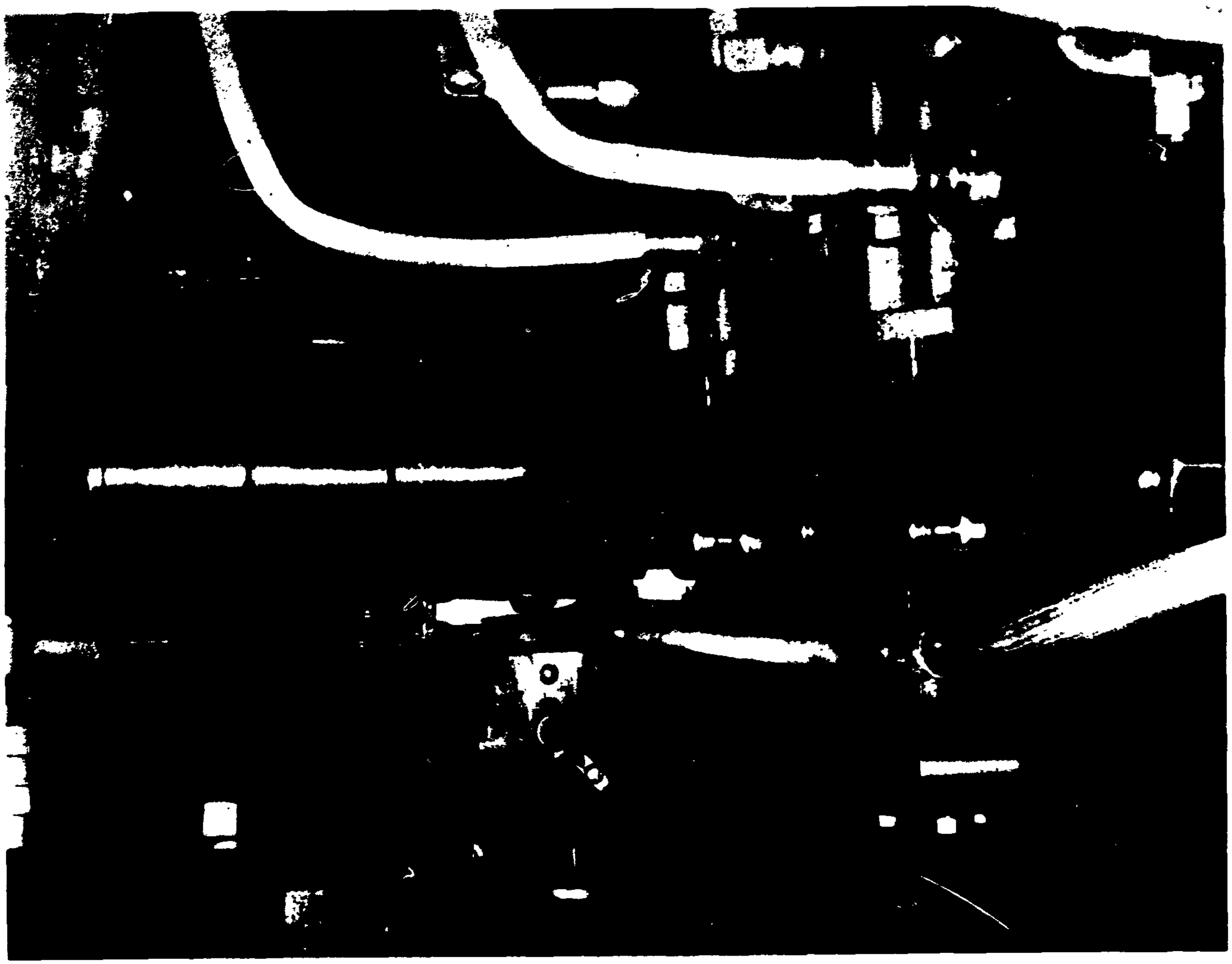


FIGURE 194

MACHINING THE "T" EXTRUSION OPERATION NO. 2

Hold-Downs, Workpiece, Electrode, Return Conductor, Cutter

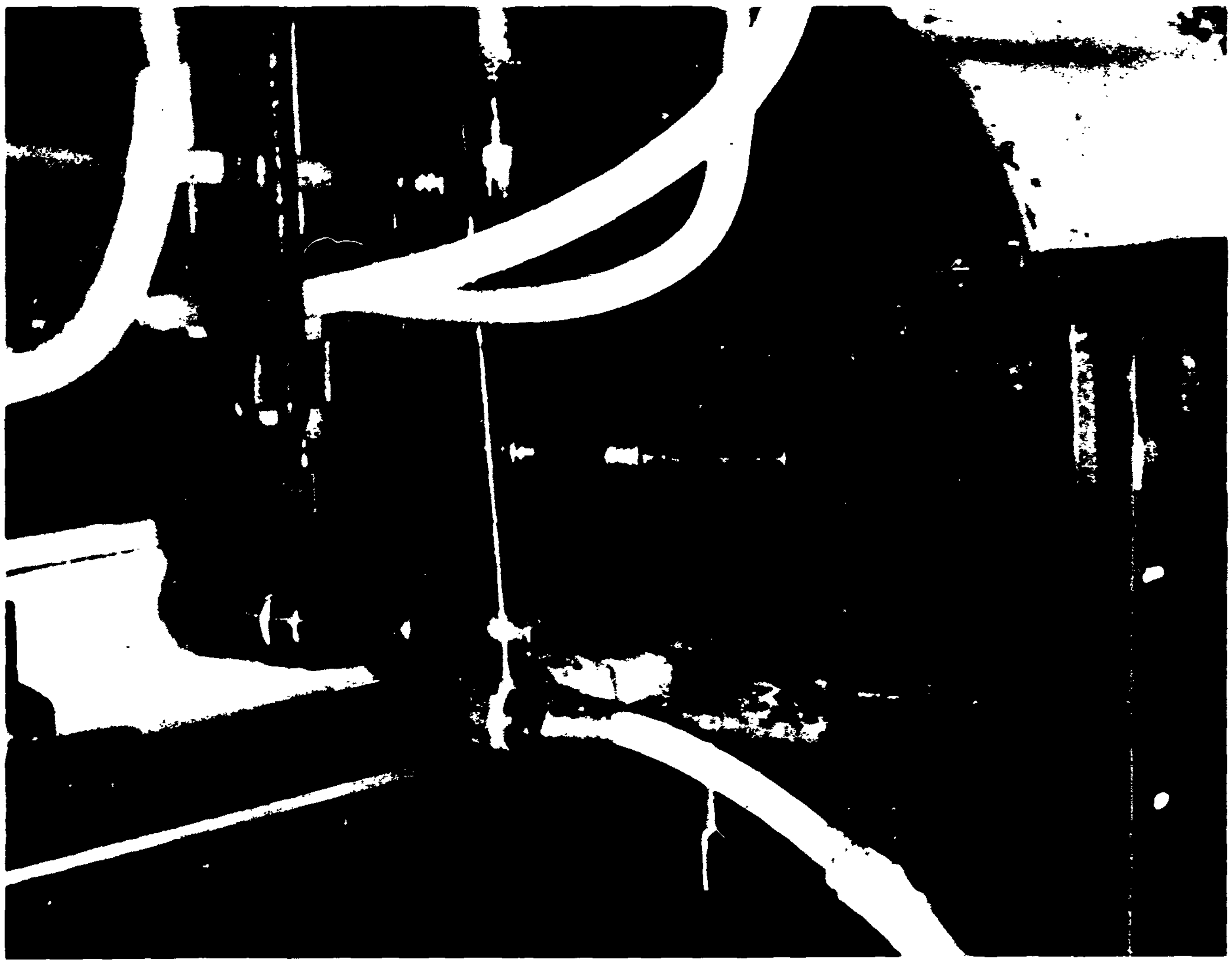


FIGURE 195

MACHINING THE "T" EXTRUSION OPERATION NO. 2

Electrode, Workpiece, Fixture, Cutter

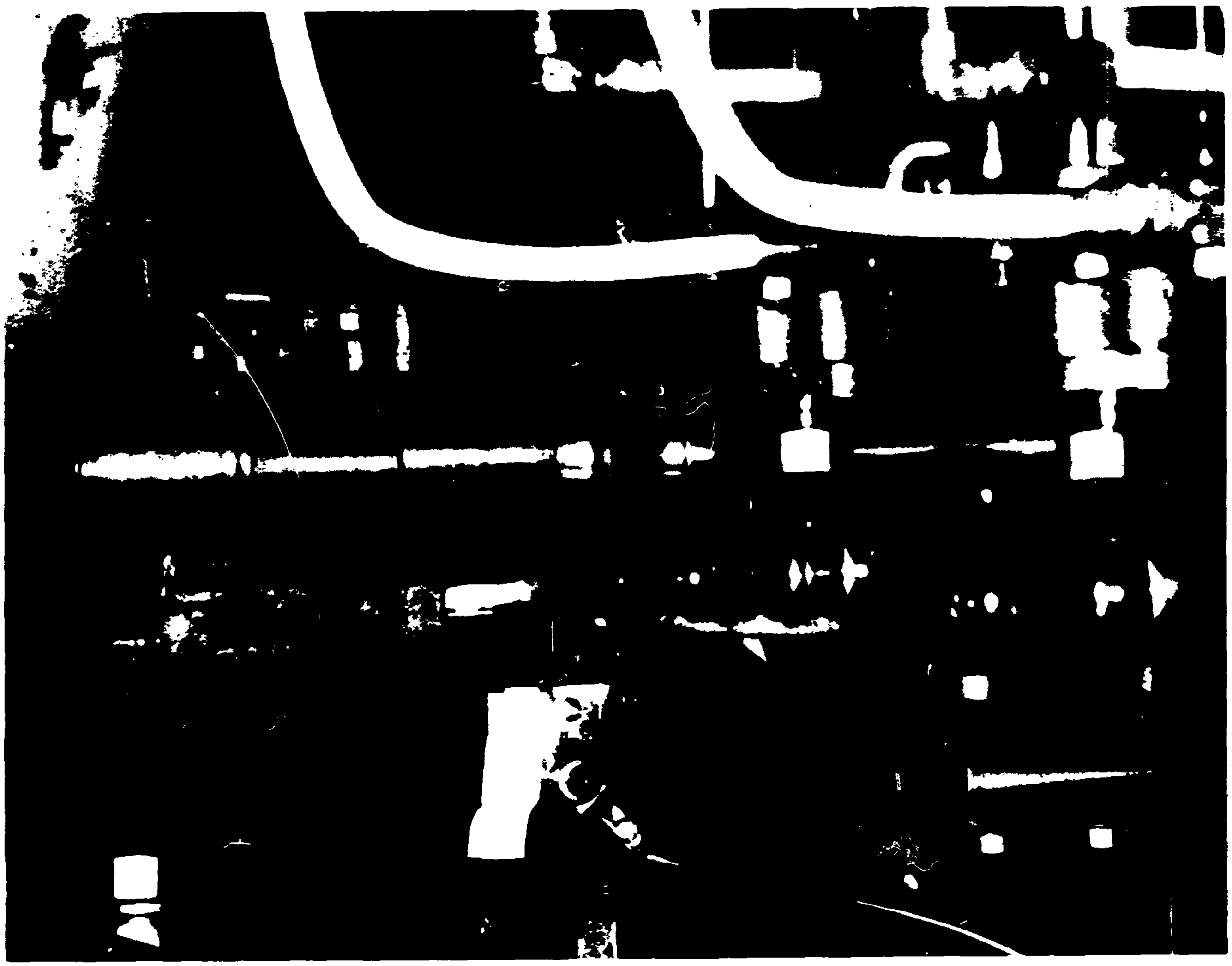


FIGURE 196

MACHINING THE "T" EXTRUSION OPERATION NO. 3

Workpiece, Electrode, Return Conductor, Cutters

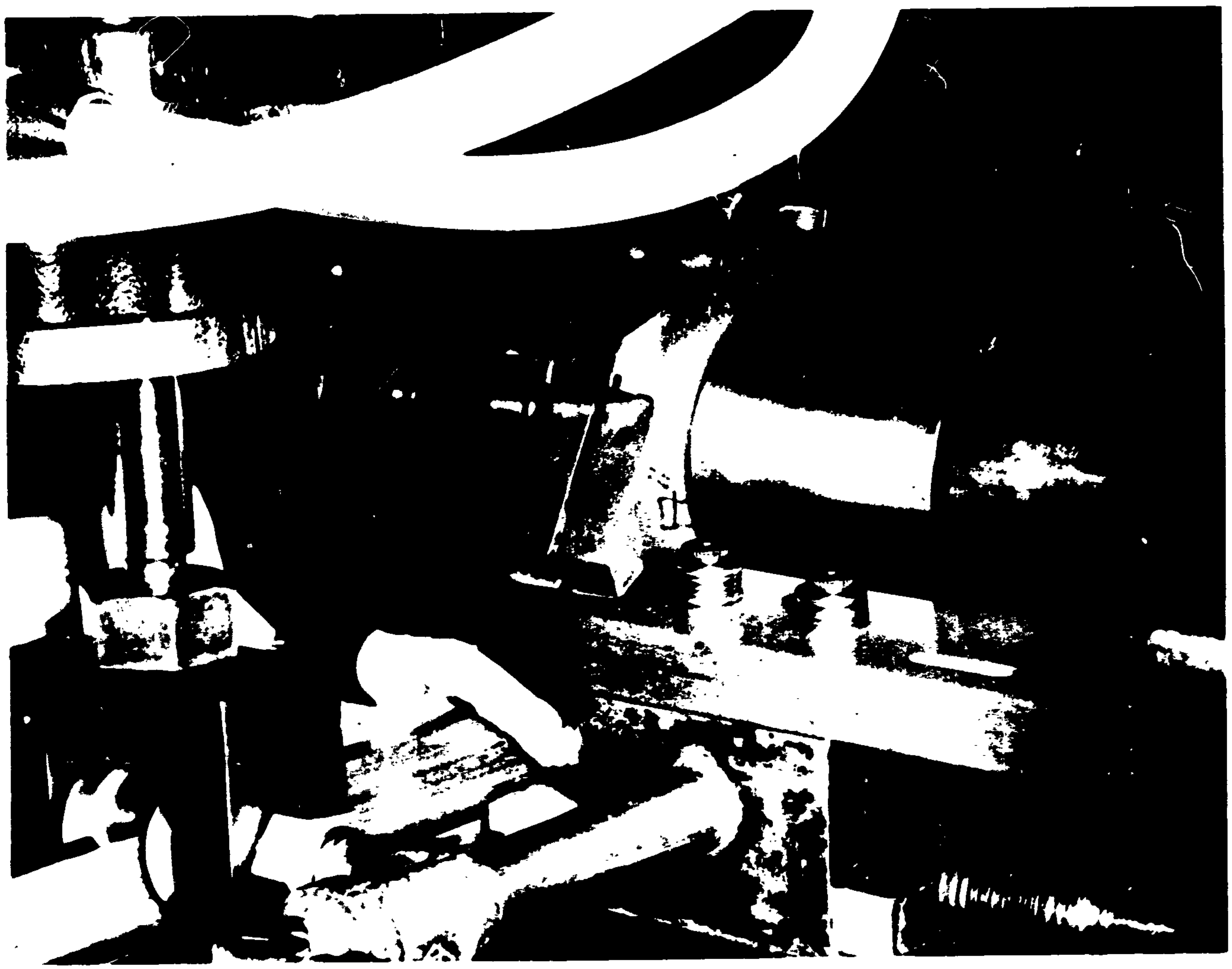


FIGURE 197

MACHINING THE "T" EXTRUSION OPERATION NO. 3

Electrode, Workpiece, Cutters

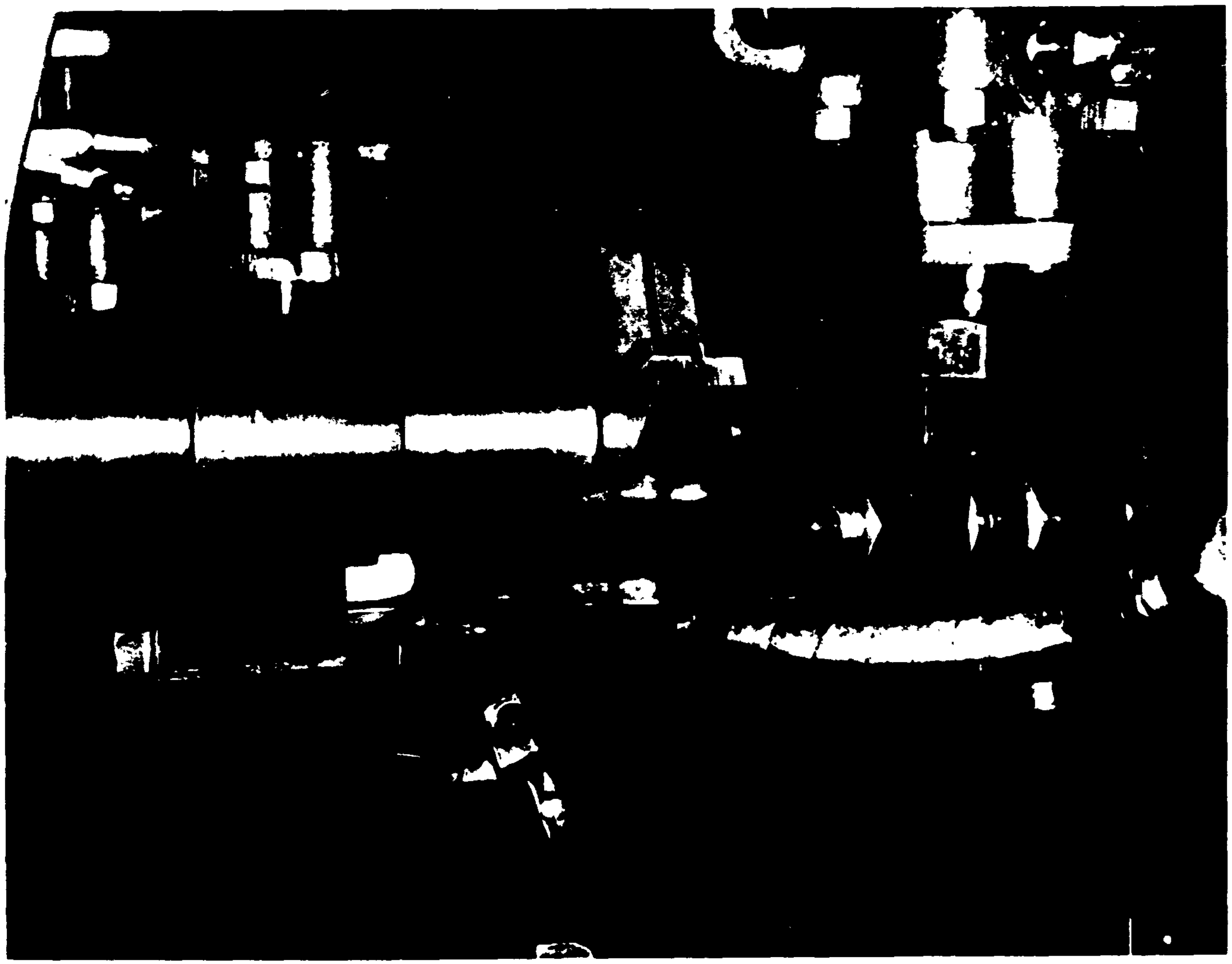


FIGURE 198

CUTTERS FOR MILLING PH 15-7 MO "T" EXTRUSION

Ph 15-7 Mo - 176 BHN Tool Material: Brazed
78B Carbide, Chip Remover - Cutter Edges
Dubbed .003 x 45° down milling 1-1/2" arbor

Operation No. 1 - Milling "T" Extrusion Base and Base Width

3 Cutter Gang (matched cutters)

	Right Hand	Center	Left Hand
Diameter	4"	3.5"	4"
Width	1/2	.750	1/2
No. teeth	8	6	8
Axial Rake	+5°	+5°	-5°
Radial Rake	0°	0°	0°
Clear	5°	5°	5°

Operation No. 2 - Milling Top of "T" Rib to Dimension

	Single Cutter
Diameter	3.5
Width	.750
No. Teeth	8
Axial Rake	+5°
Radial Rake	0°
Clear	5°

Operation No. 3 - Milling Rib Width and Top of Base to Dimension

2 Cutter Gang (matched cutters)

	Right Hand	Left Hand
Diameter	4"	4"
Width	1/2	1/2
No. Teeth	8	8
Axial Rake	+15°	-15°
Radial Rake	0°	0°
Clear	5°	5°
Radius	1/16	1/16

FIGURE 199

COST OF THE HOT MACHINING SET-UP
"T" Section Extrusion

Part	Design Hours	Design Cost	Your Deisgn Cost	Construc-tion Hours	Construc-tion Costs	Your Const. Cost	Materials
Front and Rear Bracket	35	$350		75	$ 750		$ 50
Fixture operations 1 and 2	20	200		45	450		25
Fixture operations 3	12	120		25	250		15
Cutters							125
Electrode air cylinders and equipment							70
Transmission Lines	1	10		6	60		55
Return Conductor (2)	4	40		15	150		5
Total	72	$720		166	$1660		$235

Total $2615

FIGURE 200

TIME STUDY AND COST DATA
"T" Section Extrusion

Machining the Base and Sides of the Base

Elements		500°F	Room Temperature
Load and Unload		5.90	5.90
Start and Stop		.11	.11
Set to Cut		.80	.80
Set to Heat		.32	-
Return Table		.45	.45
Cutting		3.69	7.10
	Total	11.27	14.36
	Set-Up	60	50

Machining the Top

Elements		500°F	Room Temperature
Load and Unload		3.50	3.50
Start and Stop		.11	.11
Set to Cut		.80	.80
Set to Heat		.32	-
Return Table		.45	.45
Cutting		3.69	7.10
	Total	8.87	11.96
	Set-Up	40	35

Machining the Sides

Elements		500°F	Room Temperature
Load and Unload		1.05	1.05
Start and Stop		.11	.11
Set to Cut		.80	.80
Set to Heat		.32	-
Return Table		.45	.45
Cutting		3.80	9.05
	Total	6.53	11.46
	Set-Up	30	25

FIGURE 201

TIME STUDY AND COST DATA
"T" Section Extrusion

Total Time	500°F			Room Temperature		
Operation	Units	Cost at $.181/min	Your Cost	Units	Cost at $.167/min	Your Cost
Operation No. 1	11.27			14.36		
Operation No. 2	8.87			11.96		
Operation No. 3	6.53			11.46		
Total	26.67	$ 4.83		37.78	$ 6.31	
Set-Up						
Operation No. 1	60			50		
Operation No. 2	40			35		
Operation No. 3	30			25		
Total	130	$23.53		110	$18.37	

FIGURE 202

COMPARISON OF COSTS

102' of "T" Extrusion

	Elevated Temperature 500°			Room Temperature		
	Units	Cost at .181/min	Your Cost	Units	Cost at .167/min	Your Cost
Set-Up	130	23.53		110	18.37	
Loading and Handling 6 x single rate	93	16.83		88	14.70	
Cutting time $\frac{12 \times 102}{27}$ x single rate	507	91.77		1051	175.52	
	730	132.13		1249	208.59	

FIGURE 203

DO NOT SCALE DRAWINGS
BREAK ALL SHARP CORNERS UNLESS OTHERWISE SPECIFIED
COUNTERSINK ALL N.C., N.F. & N.S. TAPPED HOLES IN FINISHED SURFACES

ALL DIMENSIONS ± .010
EXCEPT RADII ± .030

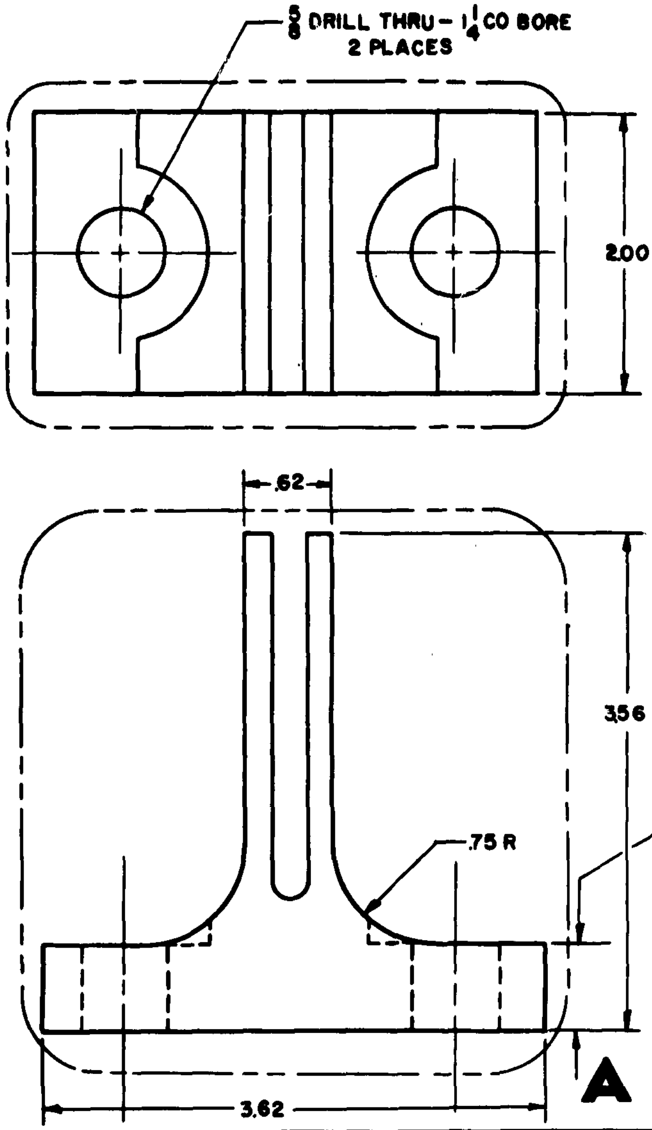


FIGURE 204

FITTING TO BE MACHINED AT ROOM AND ELEVATED TEMPS.

LETTER	NOTICE	DATE	CHANGE

SCALE — LIMITS OF FRACTIONAL DIMENSIONS ARE + OR – 1/64 UNLESS OTHERWISE SPECIFIED

DRAWING OR PART NAME: **FITTING**

MACHINE				
UNIT	QUAN.	MATERIAL	MAT'L SIZE	HEAT TREAT.
DRAWN BY: G RUSS	DATE: 11-3-61	RENE' 41		
DRAW. CH. BY	DATE			
TR. BY	STDS.			
TR. CH. BY	APPROVED	SUPERSEDES		ASSEM. NO.
THE CINCINNATI MILLING MACHINE CO.		SUPERSEDED BY		

0 1 2 3 4 5 6

CONCLUSIONS

The major conclusion that may be drawn from this study is that hot machining can reduce costs and increase productivity in the aerospace industry if it is properly applied to suitable jobs. This conclusion is supported by the following secondary conclusions.

(1) The cost of turning certain hardened alloy steel parts can be reduced by utilizing elevated temperature machining. Reduction in set-up costs can be obtained.

(2) The cost of milling previously heat treated materials can in many cases be materially reduced by elevated temperature machining. Proper planning of set-up and sequence of operations such as that exemplified in the machining of solution treated Ph 15-7 Mo, "T" section extrusions, materially influences the final cost.

Machinability tests on Rene' 41 at elevated temperatures show that no face milling tool life improvement over room temperature is obtained unless the workpiece is narrower than two inches. No tool life improvement was obtained when turning a Waspalloy forging at various elevated temperatures.

In turning, tool life improvements of 5 to 40-fold were achieved when cutting 17-4 Mo, AISI 4340, 17-7 Ph, and Thermold J at elevated temperatures up to 900°F.

In face milling, tool life improvements at 1000°F to 20 times and 100 times that obtained at room temperature were achieved on 17-4 Mo (380 BHN) and Thermold J (390 BHN), respectively. A limiting temperature is reached when welding occurs between chip and tool; this occurred around 1100°F in these tests.

Radio-frequency resistance heating was found to be practical for heating magnetic materials for turning and milling.

Inert tungsten arc heating has proved satisfactory for face milling and turning operations on non-magnetic materials. When used with inert atmosphere, inert arc heating can be used on refractory metals.

Except in isolated cases where limited success was obtained, high temperature machining of refractory metals and titanium alloys can offer no advantages over room temperature machining with appropriate cutting fluids.

No detectable change in microstructure was apparent on examination of hot machined specimens, but microhardness checks showed tempering to occur when the tempering temperatures had been exceeded. The depth to which tempering occurs varies with the material and duration of heating. Surface finish was as good or better at the elevated temperature than at room temperature, though some surface oxidation was apparent at the higher temperatures used. Workpiece distortion presents a problem which can be overcome by better localization of heat.

There are no excessive safety or health hazards involved in hot machining, generally, and there are many ways available of controlling the heat source.

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ACKNOWLEDGEMENTS

We wish to publicly thank the following companies and individuals who have helped in one or more of the various phase of this project by contributing reports, material, discussion and suggestions on the problems of hot machining:

Aerojet-General, Inc., Sacramento, California
R.H. Patchen, Production Engineer
I. J. Stewart, Fabrication Research Engineer

Allison Division of General Motors Corp., Indianapolis, Indiana
E.D. Berlin, Head, Experimental Process Development
L.E. Batchelor, Master Mechanic

Boeing Airplane Company, Aero-Space Division, Seattle, Washington
A. L. Pickrell, General Supervisor
J. L. Phillips, General Supervisor
W. J. Maxson, Manufacturing Research
H. Hanson, Manufacturing Development
R. Hanger, Manufacturing Development
L. Champoux, Metals Unit

W.W. Cargill, Jr., 7411 West 85th Street, Los Angeles 45, California

The Cleveland Twist Drill Co., Cleveland, Ohio
E. Brezina, Manager, New Product Development
N. Marrotte, Manager, Metallurgical Research

Convair Division of General Dynamics, Inc., San Diego, California
A. Crum, Ass't. Manager, Mfg. Development Group

Ford Motor Company, Dearborn, Michigan
A.E. DiGregorio, Manager, Manufacturing Improvement

General Electric Company, Evendale, Ohio
E.S. Jones, Manager, Alloy Studies
Dr. W.H. Chang, Consulting Metallurgist
E.N. Bamberger, Metallurgical Engineer
E.R. Lehman, Metallographer
M. Miller, Metallographic Technician

Linde Company, Division of Union Carbide Co., Cincinnati, Ohio

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Lockheed Aircraft Corporation, California Division, Burbank, California

R.L. Vaughn

J.W. Nicholas, Group Engineer, Producibility Methods

G.P. Clemens

Menasco Manufacturing Co., Los Angeles, California

H.E. Schweigler

Metcut Research Associates, Cincinnati, Ohio

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Dr. J.F. Kahles, Vice President and Director of Metallurgical Research

Norair Division of Northrop Corp., Hawthorne, California

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V.L. Boland

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T.M. Rothrock

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North American Aviation, Inc., Los Angeles, California

M. Westerberg, Supervisor, Tool Design

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Sam Tour and Co., New York, New York
Sam Tour, President

Spring Garden Institute, Metal Removal Center, Philadelphia, Pennsylvania

State University of Iowa, Iowa City, Iowa
E.M. Mielnik, Professor of Mechanical Engineering

Vought Aeronautics Division of Chance Vought Aircraft Corp., Dallas, Texas
J.F. Shea, Supervisor, Manufacturing Methods and Equipment Planning

Warner and Swasey Co., Inc., Cleveland, Ohio
R.T. Hook, Chief Metallurgist

Wha Chang Corporation

Assistance in this research work has also been rendered by the following members of The Cincinnati Milling Machine Co.:

Metallurgy Department
A.L. Hartley
M.C. LauBau

Meta-Dynamics Division
W.F. Hall
L.F. Dugle

Time Study Department
- N.R. Ribariu
- N.F. Inskeep
- C.H. Kraus
- R.H. Hunter

Planning Department
- W.H. Wellman

Tool Design Department
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